AFCRL-63-51
FEBRUARY 1963

63-3-2

403 987

Research Report

Modern Antennas for Space Communications

C.J. SLETTEN

ELECTROMAGNETIC RADIATION LABORATORY PROJECT 4600

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES, OFFICE OF AEROSPACE RESEARCH, UNITED STATES AIR FORCE, L.G. HANSCOM FIELD, MASS.

Best Available Copy

AFCRL-63-51
FEBRUARY 1963

Research Report

Modern Antennas for Space Communications

C.J. SLETTEN

ELECTROMAGNETIC RADIATION LABORATORY PROJECT 4600

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES, OFFICE OF AEROSPACE RESEARCH, UNITED STATES AIR FORCE, L.G. HANSCOM FIELD, MASS.

Abstract

Research trends in antenna design stress the probability that space communication and detection functions of future systems will depend on giant-aperture antennas operating at several hundreds of megacycles per second.

The design principles and merits of large-acreage antennas such as spherical reflectors, paraboloidal reflectors, parabolic cylinder antennas, flat antenna arrays, and interferometers are reviewed, with particular attention to the new multiplate antenna design.

The electronic scanning methods of antennas and arrays that are compared include some advanced designs for nonlinear antennas.

New techniques of multibeam generation and antenna pattern optimization are suggested for improving the aperture efficiency and information-gathering capacity of future radio and radar space telescopes. To achieve these and other desirable improvements in the performance of space antennas, focal region research is important.

Preface

I wish to express my appreciation to members of the Electromagnetic Radiation Laboratory and others on the AFCRL staff who helped me with the manuscript; I am especially indebted to Dr. L. M. Hollingsworth, Dr. F. S. Holt, Mr. C. E. Ellis, Jr., Dr. A. C. Schell, and Mr. P. Blacksmith, Jr., for constructive criticism and corrections. My apologies to those workers whose contributions have added to the scientific substance and ideas reported in this survey but who remain unacknowledged because some of the ideas and inventions are of complicated or unknown origin. Many important recent antenna contributions are omitted for reasons of security or because they lack a close relation to the space application theme.

An abridged version of this survey appeared in Electronics 35(No. 36):39-48. September 7, 1962.

Contents

Illustrations

Modern Antennas for Space Communications

1. TRENDS IN ANTENNA TECHNOLOGY

Most modern systems for search and communication used by man to augment his own biologic senses have no sensory organs other than the antenna. . elligence obtained through space exploration with missile probes and electromagnetic telemetry, or with radar and radio astronomy equipment that is earth-based, can be conveyed only through the antenna's response to electromagnetic waves. The dominant dependence of space systems upon antenna performance was pointedly illustrated by our Pioneer V space probe, which relied heavily on Jodrell Bank's 250-ft antenna.

The forces driving antenna technology toward new forms and new capabilities are economic as well as scientific and military. Economic pressure will eventually steer us to direct "natural" answers. The sophisticated "ultimate" systems of great versatility and high cost will inevitably be replaced by simpler antennas performing a diverse number of functions economically.

1.1 Antennas for Space Needs

The further we penetrate into space—to locate and communicate with our space vehicles—to seek explanations of the strange noisy signals that emanate from cosmic processes in our solar system and interstellar space—to examine the nature. structure, and physics of the universe—the wider the range and the higher the

Released for publication September 1962.

resolving power demanded of antennas. Powerful radars capable of reflecting detectable signals from distant planets require extremely large antennas with large effective apertures.

Figures 1 and 2 show how aperture size, frequency, and dimension tolerances affect antenna performance.[1,2] Antenna size cannot be increased arbitrarily. Engineering constraints exist. A method must be available for distributing or gathering radiation from large antenna apertures, with low loss and coherent phase. Below frequencies of about 500 Mcps, radiating elements can be effeciently fed by transmission lines; above these frequencies, shaped reflector surfaces fed through the air by techniques similar to those used with optical reflectors are usually best. For the antenna aperture to be used effectively, most sections of such reflector surfaces must be held to within $\lambda/8$ of the design dimensions.

Fortunately, space antennas require no elaborate rapid beam-steering capability. Objects or radio sources in outer space cannot have large angular velocities relative to an observation point on earth, and so the principal scanning problem is one of counteracting the rotation of the earth. Since most scientific investigations deal with the plane of the ecliptic, space antennas should have horizon-to-horizon scan in the east-west plane; a modest scanning ability suffices in the north-south direction. A more vexing problem in searching and mapping the vast heavens is to measure the true bearing of the extremely narrow antenna beams.

Several proposed techniques for devising antennas to meet these functional demands are discussed in this paper. The usable radiofrequencies are restricted by the losses, refraction, and scintillation caused by the earth's atmosphere and the ionosphere. Random fluctuations in the veiling gases in these regions may set an upper bound on antenna size much as 'seeing' does in the case of optical lenses. For the foreseeable future, however, the fundamental constraint appears to be one of cost. The designer that achieves a satisfactorily performing aperture at a low cost per unit area will have removed the main obstacle to deep space penetration.

1.2 Antennas for Mapping and Reconnaissance

Optical observations of objects on the surface of the earth or planets are critically dependent on weather conditions and sunlight. Microwave and radio-frequency radar waves can penetrate clouds but the angular resolution attainable with vehicle-borne radars has been restricted by the small size of the antennas. The direct approach of incorporating hugh antennas into vehicles has been unsatisfactory. The smooth trajectory of space vehicles offers the use of synthetic-aperture antennas as a more attractive means of achieving high-resolution vehicular antennas. This work has been rather completely reported in Vol. MIL-6, No. 2, IRE Transactions on Military Electronics, April 1962. (See especially pages 111-121.)

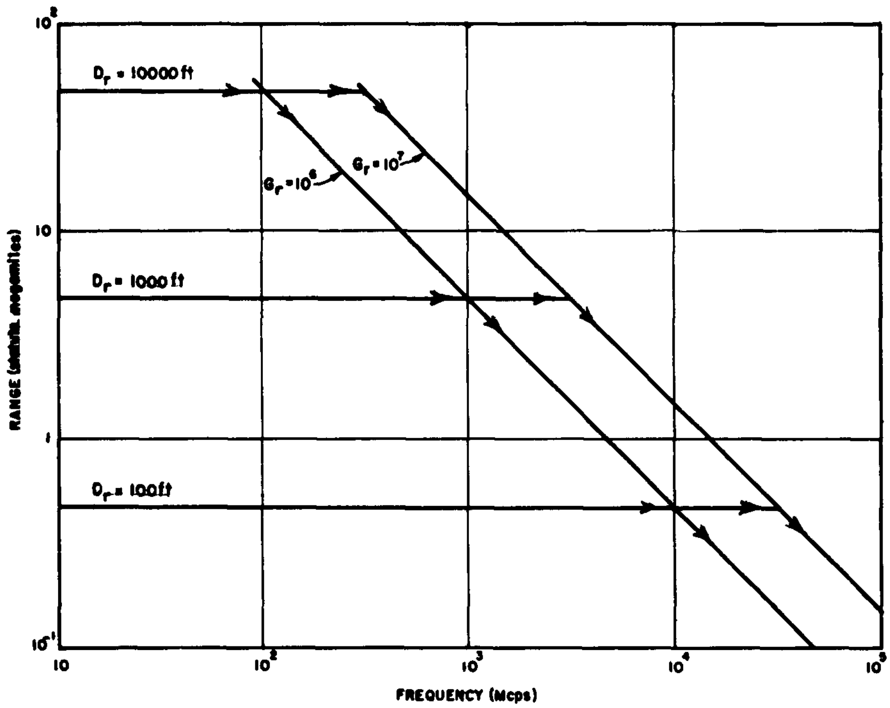


FIG. 1. Advantage of Large Antenna Apertures for Achieving Maximum Communication Range. Under the conditions specified, the communication range in megamiles depends only on the size of the aperture; it is independent of the operating frequency. In these curves, which apply particularly to space probes with unstabilized vehicles requiring near-omnidirectional antennas,

$$R = \frac{D_r}{4 \cdot 5280 \cdot 10^6} \sqrt{\frac{P_t G_t}{P_r}} \ .$$

where

R = range in statute megamiles
G_t = transmitting antenna gain
D_r = receiving antenna diameter in feet
$\frac{P_t}{P_r} = \frac{\text{power transmitted}}{\text{power received}}$.

It is assumed that $G_t = 1$, and $P_t/P_r = 10^{16}$, and that reflector tolerances limit the maximum gain G_r of the receiving antenna.

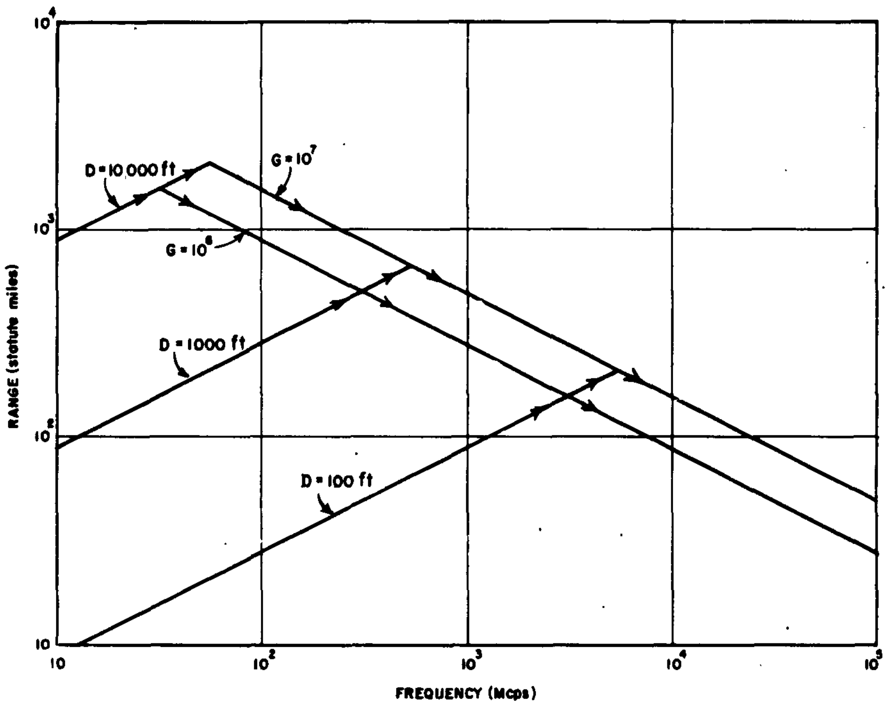


FIG. 2. Relation of Antenna Aperture Size to Radar Range. For the representative radar parameters shown, the larger antenna aperture sizes still have an important range advantage. Considering other factors such as powers available at different frequencies, ability to seek and acquire targets, and construction costs, the giant aperture at a lower frequency is usually the choice for deep space probes. In the curves shown,

$$R = \frac{1}{5280} \sqrt[4]{\frac{P_t \sigma G A}{P_r 16\pi^2}} ,$$

where

R = range in statute miles
G = antenna gain
A = antenna aperture in square feet
D = antenna diameter in feet
σ = target backscattering cross section in square feet
$\frac{P_t}{P_r} = \frac{\text{power transmitted}}{\text{power received}}$.

The quantity $P_t\sigma/P_r$ is set equal to 10^{16}. It is assumed that the transmitting and receiving antennas are identical and that

$$G = \frac{4\pi A}{\lambda^2} = \frac{\pi^2 D^2}{\lambda^2} = \frac{\pi^2 f^2 D^2}{c^2} .$$

It is also assumed that reflector tolerances limit the maximum gain of the antenna.

In addition to high angular resolution and gain from microwave antennas, aerial mapping and space reconnaissance by radio astronomy require optimization of the antenna pattern for the type of extended targets to be resolved. For adjusting resolution versus contrast to obtain the best 'picture,' antenna designers have borrowed heavily from the techniques of optical designers, using 'apodization' (deliberate blocking) of the lens aperture to enhance detail or certain spatial frequencies in the image. The phase and amplitude distributions across the gathering apertures, however, are better controlled through electromagnetic techniques. Workers at both optical and radio wavelengths have found it useful to express the antenna (or lens) response to objects in terms of transfer functions rather than to depend on the usual antenna or diffraction pattern since this mathematical representation of how an antenna responds to a complex distributed source exhibits the needed antenna characteristics more simply than the usual radiation patterns.

1.3 The Upward Look

Since air-breathing vehicles must remain relatively near the surface of the earth, the elevation angles for radar detection of aircraft and communication with them from the ground are mainly near the horizon. Communication between ground stations via the ionosphere requires antennas whose beams can be concentrated along the horizon and perhaps scanned in azimuth. The obvious requirements have been met by the use of circular arrays or Wullenweber antennas for azimuth-scanning, $\csc^2\theta$ patterns on search radars looking along the earth's surface, and antennas on high towers for azimuth-scanning over low elevation angles. The achievement of elevation angle accuracy at low angles is still a problem on most systems.

Now that ballistic missiles, satellites, and space ships can be located at great distances from the antenna at high elevation angles as well as at low, hemispheric coverage as well as improved horizon coverage is needed. The search for missiles, satellites, and space rockets has contributed to the trend toward a basic change in the antenna's physical attitude—the antenna flat on its back looking zenithward is as useful for military purposes as it is for those of radio astronomy. Moreover, parameters of the space era demand bigger antenna apertures in new configurations relative to the earth. The practical solution: big antennas for space surveillance built along the surface of the earth.

1.4 Prospects in Communications

The manifold applications of artificial earth satellites bring us to the threshold of a new era in radio and television communication. The gain, frequency, and scanning characteristics of antennas designed for earth-satellite communications will depend on whether dipole belts, active relay satellites, or passive reflectors, are selected as the most feasible for military and commercial traffic. Even the synchronous so-called 'stationary' satellites will move slightly with respect to the contacting ground station and require some beam-scanning for angular coverage.

Future satellite antennas and passive reflectors may be light-weight unfurlable types that take permanent geodesic form upon inflation or ejection from compact cannisters after being launched into the weightless vacuum of space. Another prospect is the use of submillimeter infrared and optical wavelengths for communication between space vehicles.

1.5 Antennas for Low-noise Receivers

Antenna surfaces are inherently 'cold' in that they produce very little of the thermal noise that enters the receiver. The antenna must be so designed and situated as to protect the receiver (antenna terminals) against thermal radiation from unwanted directions. Pertinent factors are antenna siting, edge diffraction from apertures, and antenna feed spillover. Unaccountably, the elimination of site reflections is a problem that has received haphazard consideration—it seems to be common practice to measure antenna patterns on especially 'clean' antenna ranges that approximate freespace and then locate antennas near buildings, towers, or hills that cause spurious lobes and pattern distortion.

In view of recent advances in rocketry and space technology that have profoundly affected radiating (and hence antenna) systems, the problem of thermal noise injection through the antenna cannot be so easily ignored as other aspects of antenna-siting have been. The maser, a low-noise solid-state receiver that reduces the noise figure of the communicator or radar receiver to less than that of the antenna and its environs, has had an important effect on antenna design. To protect the maser from hot sources on the earth or in the sky, the total spherical angular response of the antenna must be controlled. All lossy paths leading to the receiver must be eliminated. For large-aperture antennas that are of necessity mounted on the ground, the nearby terrain could be smoothed to act as a perfect reflector at the low angles seen from the antenna. Such reflecting surfaces would reflect the spillover, or edge-diffracted energy, toward the cold radio sky. This optical property of smooth flat surfaces is commonly seen in the specular reflection from a smooth flat highway.

1.6 Variable-focus Antennas

It is not generally appreciated that focused-aperture antennas can transmit power with efficiencies of over 50 percent when they are located in the nearfields of each other. From the usual definition of the nearfield,

$$R \leq \frac{2D^2}{\lambda} ,$$

where R is the range of the nearfield, D is the aperture diameter, and λ is wavelength, we see that there are antennas today that have nearfield regions extending several hundred miles. Focused-aperture microwave antennas could therefore be among the most practical for transmitting electrical energy between points on earth or from earth to space. For identification of objects in the lower atmosphere, an antenna focused in its near zone can locate and resolve the angular position of a missile or target much more accurately than an antenna focused at infinity.

1.7 Functional Demands

The difficulties confronting the present-day antenna designer are compounded by the ever-increasing need to accelerate the gathering of information. The number of man-made objects orbiting the earth is rising rapidly. Faster missiles and aircraft, accompanied by debris and decoys, require greater data capacities in the antenna. Probably no functional need has motivated more antenna research than the requirement for greater antenna bandwidth. Frequency-shifting is necessary to counteract the diurnal and nocturnal vagaries of the ionosphere. Military missions often require the use and search of large regions of the electromagnetic spactrum.

A goal implicit in the quest for more information-gathering ability is the volumetric search of space consistent with the functions designed to be performed. One favored simple solution is to make the antenna as omnidirectional as theoretically possible, and when all directions in space are of equal interest this is as efficient a signal-seeking antenna as any other single-terminal antenna. Obviously, it yields no angular position data on sources of radiation and more complex antennas must be tailored to functional needs or according to known source distributions by compromises on antenna beam shape, antenna gain, signal and antenna bandwidth, time on target, and multiterminal or several-antenna operations. Under the usual conditions of single-port antenna operations, there are advantages in using lower frequencies for volumetric search of space (see Fig. 3).

It cannot be denied that antenna design is not influenced by technologic and economic considerations alone. Each bureau, agency, and industrial scientist likes to invent new antenna techniques and designs. Without a common clearing house, considerable reinvention is inevitable, but it often leads to better products. The tendency to attempt the ultimate antenna or system that will singly solve a large class of problems usually gives birth to many contracts and many disappointments in unfulfilled performance specifications, and many delays in schedules. Although efforts to combine many functions into a single antenna design are laudable, and sometimes efficient, simplicity of antenna principle and structure brings more satisfying results sooner and easier.

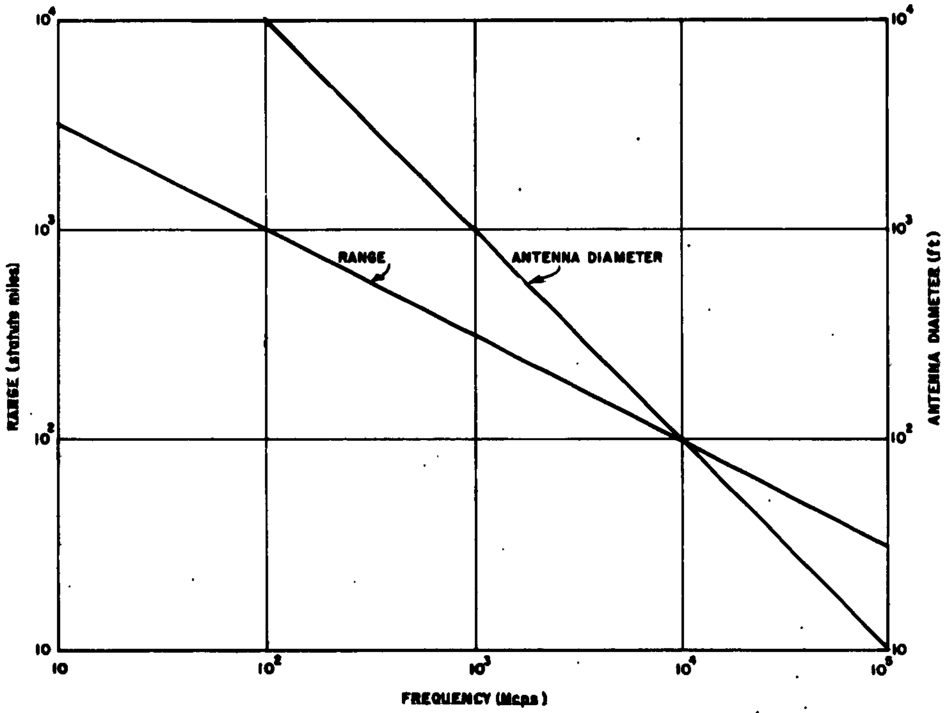


FIG. 3. Disadvantage of Higher Frequencies for Radar Search. These curves show maximum range as a function of frequency for a scanning radar system subject to the following conditions: (1) antenna gain remains constant at 67.5 db (assuming 55 percent efficiency), (2) the radar system has a range of 100 statute miles at 10^4Mcps, (3) the data rate remains constant, (4) the hits per scan do not exceed 16. The constant gain condition requires the antenna diameter to change as shown.

If a three-dimensional scanning radar system has a fixed antenna aperture area and data rate, with not more than 16 hits per scan, then the maximum range of the system will be practically independent of the frequency but the angular accuracy and resolution will vary directly with the frequency.

If, rather than a fixed antenna aperture area, the system has a fixed antenna gain, then the angular accuracy and resolution will stay fixed but the maximum range will vary inversely as the square root of the frequency. This is particularly pertinent in considering maximum-range systems since mechanical and/or electrical tolerances effectively fix maximum realizable antenna gain, independent of frequency. The price paid for increased range at the lower frequencies is increased antenna aperture area.

2. THE BIG ANTENNAS

2.1 Rotatable Paraboloidal Dishes

For both optical and radio wavelengths, the paraboloidal reflector has been developed to produce the greatest aperture gains and narrowest pattern beamwidths. The 200-in. optical (Hale) telescope at Mt. Palomar is an example. For coherent light it has a theoretical gain of 147 db and a beamwidth of $5.7^{\circ} \times 10^{-6}$ at 5000 Å. The 50-ft K_a-band radio telescope at the Naval Research Laboratory has a gain of 72 db and a beamwidth of $5^{\circ} \times 10^{-3}$, that is, 0.3'. Nothing could be simpler; the design requires only a single reflector surface that focuses to a point. For all wavelengths of interest the aperture size of the paraboloidal surface has been pushed to the limits of the materials used. Energy is collected in phase at the focus, the effective gain (electromagnetic wave-gathering power) depending on the size of the reflector and the tolerances maintained.

Because the paraboloid has a rather restricted useful field of focus, it is usually necessary to point the antenna beam or beams by rotating the entire reflector. Rotation distorts the paraboloidal surface. This tendency of materials to bend when rotated in the earth's gravitational field is a fundamental obstacle to increasing the reflector dimensions beyond their present limits, which are optimum relative to operating wavelengths.[3,4]

In terms of wavelengths of aperture, the paraboloid ranks among the giant antennas. Ways and means of increasing the size of its effective aperture have intrigued the efforts of many designers. One approach has been to compensate mechanically for the flexure deformation caused by weight. Design studies on 300- and 600-ft reflectors have tested the feasibility of mechanical adjustments as the reflector assumes different attitudes.[4,5] To protect their 120-ft paraboloid from the effects of large variations in temperature or wind pressures, Lincoln Laboratory in Lexington, Mass., have 'climatized' it with a radome.

A good method for scanning with a fixed paraboloid (Fig. 4) is provided by the design[6] used by Kraus of Ohio State University. Scanning in the north-south direction is achieved by tilting a flat plate or mirror in front of a fixed paraboloid mounted over a ground plane on the earth. Limited scanning in the east-west plane is achieved by moving the antenna feed. In its present form the antenna requires two reflector surfaces. Mechanical sagging is a problem that goes with the size of the tilting mirror.

2.2 Wide-angle Reflectors

In single-surface and paraboloidal reflector design it is remarkable that more attention has not been given to widening the focal plane to permit scanning by feed

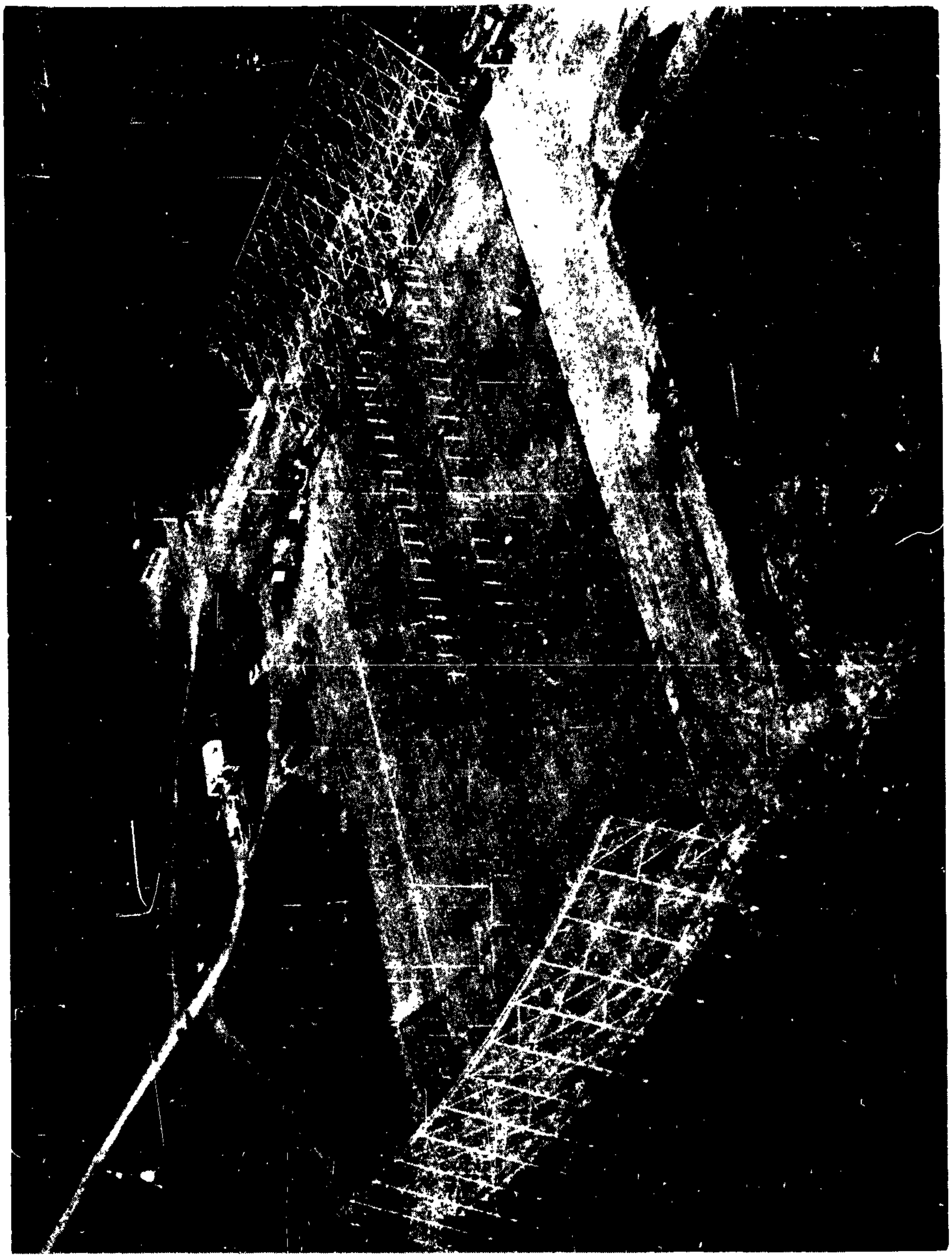


FIG. 4. [illegible]

motion alone. One notably successful example of improvement in wide-angle capability of reflector antennas is the NRL-pioneered parabolic torus antenna[7] whose reflector surface (Fig. 5) is formed by rotating a parabolic curve about a point on the parabolic axis approximately 2 focal lengths from the vertex of the generating parabola.

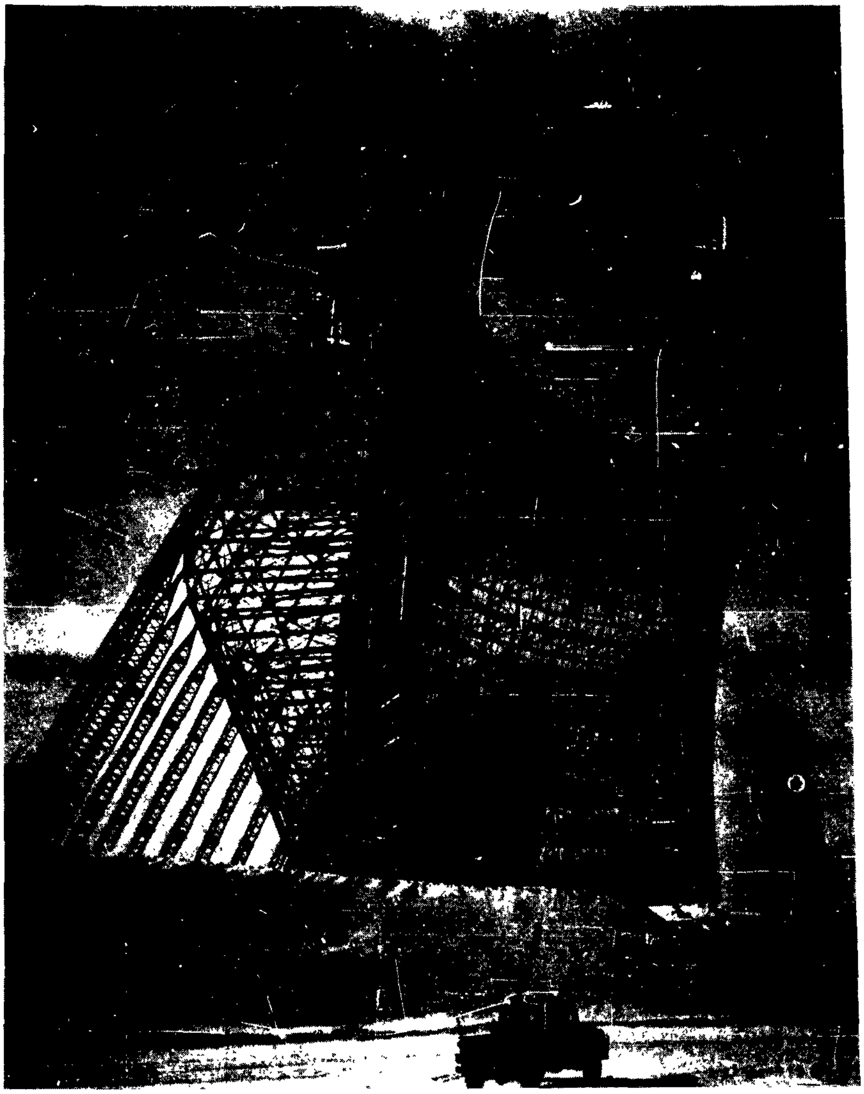


FIG. 5. Parabolic Torus Antenna Used for Air Force Ballistic Missile Early Warning

The method of sidelobe reduction illustrated in Figs. 6a and b successfully applies the 'transverse correction' technique advocated in this paper. The reflector has a wide focal region in one plane, which makes it convenient for azimuthal scan or generation

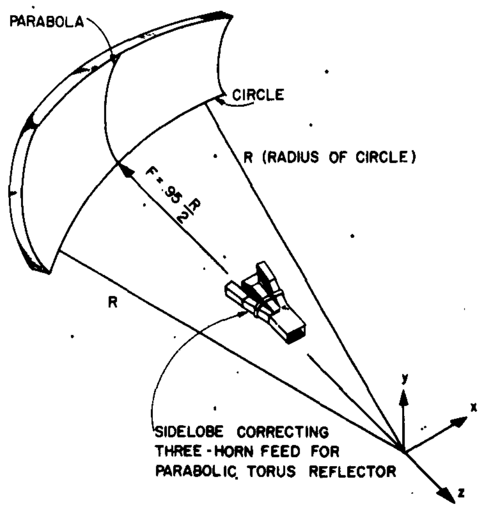


FIG. 6a. Geometry of Parabolic Torus Reflector

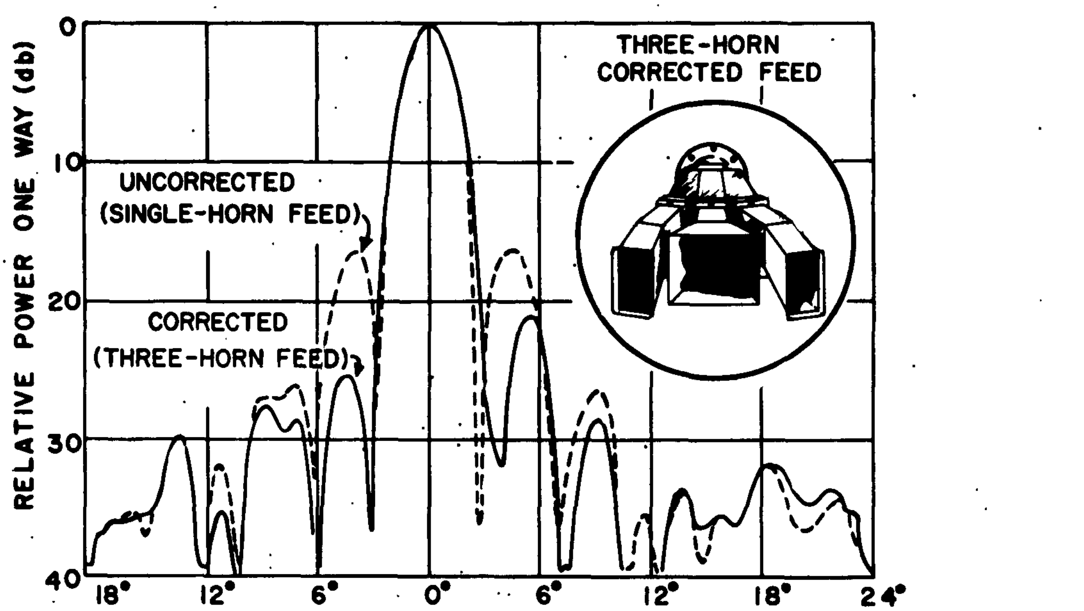


FIG. 6b. Antenna Pattern Results Showing Sidelobe Reduction

of elevation search patterns. This antenna has several interesting variants. The generating curve can be swung in a 360° arc to form a closed concave surface. When the reflector mesh is composed of rods inclined 45° with a plane through the focal region, 360° scan is possible for radiation polarized 45° from the vertical.

An exterior parabolic torus produced by rotating a parabolic curve in a circle with the focus directed outward from the center of the circle is also a useful antenna, requiring a phased line rather than a point source feed. Because these torus designs are not perfectly focused in the optical sense their usefulness as big antennas is limited.

2.3 Cylindrical Reflectors

The parabolic cylinder[8] requires a scanning line source but allows beam-steering in one plane with a singly curved reflector surface. One of the first big antennas based on this principle was VOLIR,[9] in which a wide-angle lens radiating from a line in the focus of a parabolic cylinder produced a good multilobe pattern. The success of such a design depends largely on the ingenuity of the line source design. Slotted waveguide arrays scanned by linear variation of phase velocity along the feeding guide are useful at microwave frequencies. An open structure like the trough guide[10] is also suitable because phase velocity and radiation coupling can be independently adjusted to give low ohmic losses and good impedance qualities as the beam is scanned through broadside (Fig. 7). At uhf frequencies, moving dipoles coupled to a two-wire line[11] could make a logical scanning line source (Fig. 8).

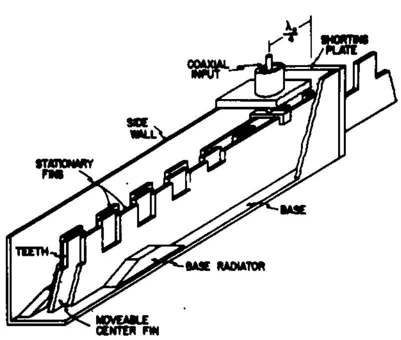
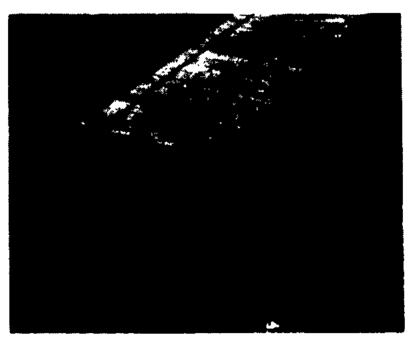


FIG. 8. Eight-element Array of Moving Dipoles Proximity-coupled to a Two-wire Line. Elements are variably spaced by 1/2-in. rubber tubing.

FIG. 7. Scannable Linear Antenna Array Based on the Trough Waveguide



2.4 Multiplate Antennas

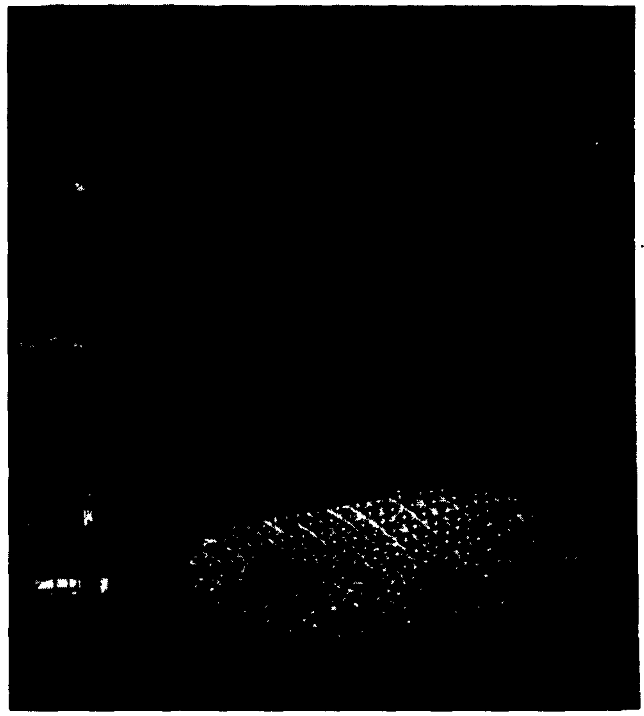
The most recent reflector system—and the one likely to provide the biggest of all antenna apertures—is the multiplate antenna.[12] The basic design is a focusing reflector constructed of many flat plates fixed to the surface of the ground along an arbitrary surface. Energy is collected in phase by rotation and translation of each reflector surface, the process producing beam-pointing. For colossal apertures, an antenna designed on these principles (Figs. 9) offers great advantages. The tolerance and motion problems are solved piecewise for flat elemental reflectors firmly fixed to the earth, and construction costs per unit area are low. Instructions for positioning each plate of the reflector are simply programed to progress regularly across the aperture; the inertia of each element is small, so scanning is rapid. There is a high frequency cutoff, which depends on the size of the plates, but a wide frequency range is available by providing translation and rotation instructions to the plates to suit the frequency. A large cone angle of the sky (half-cone angle exceeding 45°) can be scanned with little loss of aperture efficiency. The antenna can be variably focused to improve angular discrimination in the near zone, which can easily extend an earth radius or more. Fan-shaped beams can also be produced by position instructions to the plates. Substantial amounts of rf power can be fed to the antenna through multiple horns on a feeding tower. Precautions must be taken to: (1) screen the radio receiver from the warm earth seen through the interstices between reflectors, and (2) prevent the regularly stepped segments from building up far-out sidelobes or grating lobes.

Related to the multiplate antenna are several other designs also in the big antenna class. One, a spherical mirror,[13] can be corrected by stepping in $\lambda/2$ increments and making each radiating rim flat. Another is a diffraction type of antenna based on the Fresnel-zone plate and well suited to making big apertures for millimeter wavelengths. In the ECI[14] lens (Fig. 10), $\lambda/2$ phase-reversing steps give good aperture efficiency.

2.5 Fixed Spherical Reflectors

The wide-angle or broad-focusing capability of a concave spherical cap has interested optical designers for many years. For operation at optical wavelengths, the spherical aberration of this configuration can be corrected by using compensating dielectric lenses in front of and behind the approximate (paraxial) focus located one-half radius from the surface. The most successful example of this technique is perhaps the Schmidt lens.[15] Microwave lens designers have in recent years shown a revival of interest in the Mangin mirror[16] also.

Back in 1949, Spencer noted[17] that the caustic, or focal plane, of a sphere has a degenerate line along the radius in the direction of the main beam. After calculating the phase required along a line source stretching from the paraxial focus to the



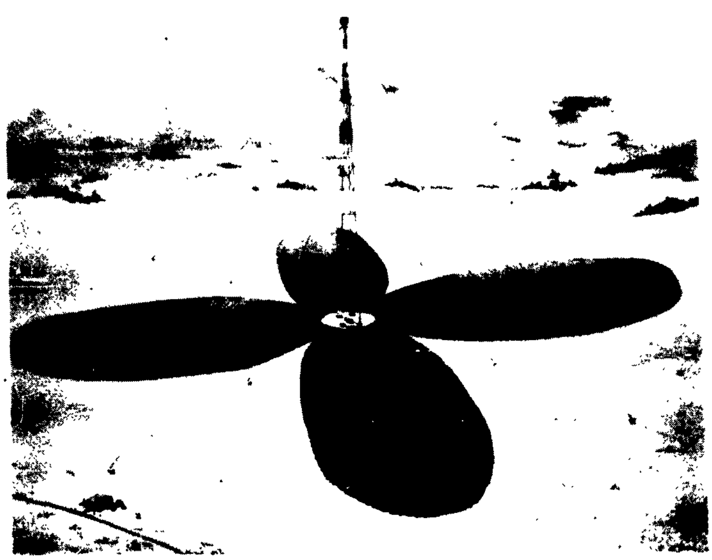


FIG. 9. Air Force Cambridge Research Laboratories Multiplate Antenna. (top) Test section at Strawberry Hill. (bottom) Artist's conception of 2400-ft scannable flat-plate array.

reflector surface to completely correct a 60° spherical cap, he suggested that at microwave frequencies the phase and amplitude distribution along the radius could be controlled by antenna array techniques. Since it requires a phase velocity greater than the velocity of light to feed such arrays near the paraxial focus, the use of waveguide was indicated.

Various waveguide feeds with slot or dipole radiators and variable-phase loading have been tested in attempts to achieve a one-dimensional or line-source corrector for the spherical cap. A representative successful design[18] has produced good patterns, with 15' of arc beamwidths. Phasing is achieved by means of a channel guide[19] with outboard feeds in the paraxial region to provide the proper amplitude taper across the aperture. A section of the circularly polarized feed designed by Technical Research Group for the 1000-ft spherical antenna of the Arecibo Ionospheric Observatory in Puerto Rico is shown in Fig. 11<u>a</u>. Design details on this type of line source are in the literature.[20-22]

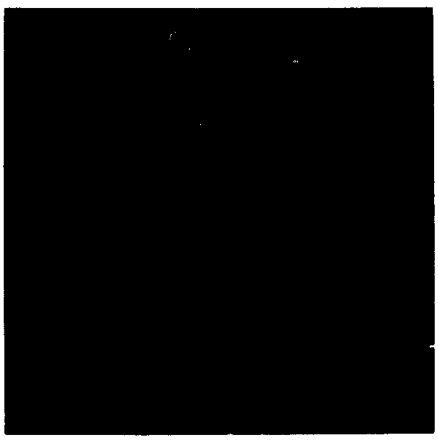


FIG. 10. Fresnel-Zone Plate Diffraction Antenna for Millimeter Wave Applications (<u>Electronic Communications, Inc., Timonium, Md.</u>

The fixed sphere that is line-source-corrected (Fig. 11<u>b</u>) can be scanned in a solid half-cone of 20° to 45° with only a small amount of aperture loss or sidelobe deterioration. The correction works perfectly in the optical sense as $\lambda \to 0$; the beamwidth or gain limit depends on the tolerances maintained in the reflector screen, precision of feed locations, and stable support. When there are large departures from the design frequency, pattern bandwidths are restricted because waveguide feeds do not keep the phase along the feed according to Spencer's curve. (A rigorous solution to the fields along the radius of a sphere has been made by Schell.) The impedance bandwidths are nevertheless good because most feed designs are traveling-wave arrays with matched loads. Wiley[23] is producing a broadband

FIG. 11a. Section of 430-Mcps Line Source Feed for Spherical Antenna (Constructed by TRG for Arecibo, Puerto Rico)

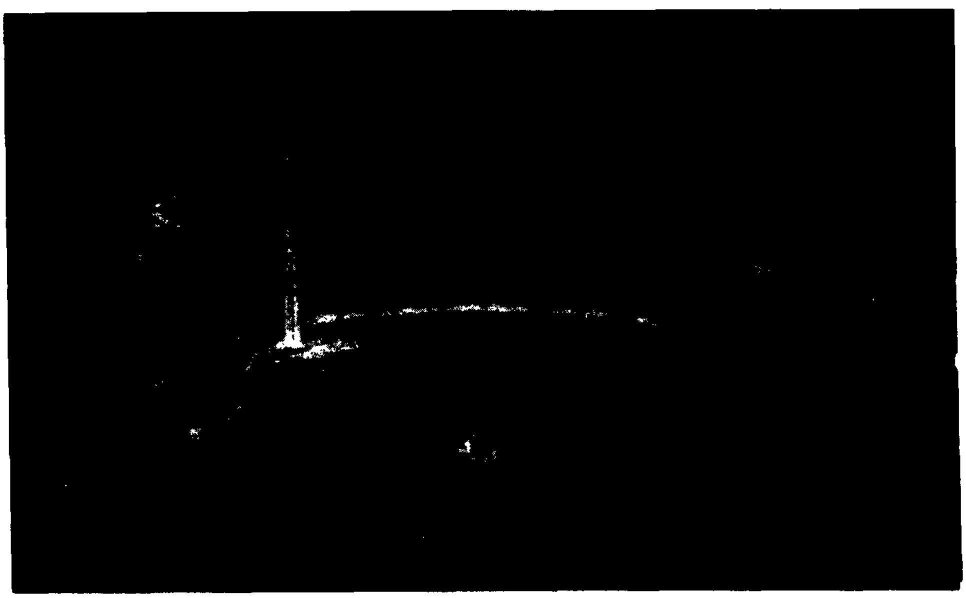


FIG. 11b. Model of 1000-ft Spherical Reflector at Arecibo Ionospheric Observatory (Sponsored by DOD Advanced Research Project Agency)

solution for phased line sources by connecting lengths of compensating line to each of the radiating elements.

In another approach to broadband feeding of a sphere, a Gregorian reflector[24] results in a system that is also perfectly correcting in the small wavelength (narrow beamwidth) limit (Fig. 12). A line source distribution of fairly arbitrary phase can in fact be produced by a generating curve fed by a point source. This design technique, first applied to correcting the sphere in 1951,* provides an excellent broadband correcting system. When the feed position and reflector size are adjusted as compactly as possible for minimum aperture-blocking, the corrector tends to produce an inverse aperture taper on the large spherical mirror. The high-sidelobe (-10 to -15 db) pattern is almost optimum[25] for radio astronomy purposes but not so good for radar scanning.

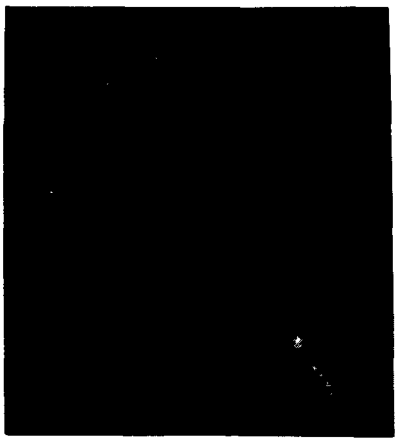


FIG. 12. Gregorian Corrector Used With Spherical Reflector Antenna to Correct for Spherical Aberrations

A variety of correcting schemes are provided by the one-dimensional (line source), two-dimensional (Gregorian corrector reflector), and three-dimensional (Schmidt lens) structures available for feeding and scanning large spheres. The transverse correction discussed in Sec. 4.2 may ultimately prove the most valuable because it allows the use of multiple (multiport) feeds to gather and process large volumes of information.

2.6 Flat Arrays

All the big antennas discussed thus far have one disadvantage in common: to achieve the optical illumination, or feeding, the feed structure must be remote from the reflector surface. Although this setup requires only optics and air (freespace) to distribute the power, it requires a tower or feed suspension to view the radiators or reflectors—and these we should like for convenience to arrange along the surface of the earth.

Alternative solutions include flat arrays fed by low-loss transmission lines, with variable phasing or feeding. Below 500 Mcps, two-wire transmission lines or coaxial cables can be used to efficiently distribute power in correct phase to dipole radiators. The very big antennas like the Mills et al. crossed array[26] and Billboard[27] have feeders and power-splitting (impedance-transforming) junctions (Fig. 13).

*C.J. Sletten, P. Blacksmith, Jr., F.S. Holt, and J.E. Holland, Line Source Antenna Arrays for Control of Pattern, Dispersion, and Phase, Technical Memo CRRD-87, 25 February 1963.

FIG. 13. Mile-long Linear Antenna Array for Navy Space Surveillance System
(Antenna Systems, Inc., Hingham, Mass.)

Despite the large choice offered by a variety of manual and solid-state phase shifters, the prospect of stationing and controlling one of these devices at each of the radiators in a large mattress type of array has so far discouraged most such attempts. Gain is proportional to the number of square wavelengths in the antenna aperture. To maintain and scan the antenna beam, both on transmission and reception, the elements must be about $\lambda/2$ apart. For scanning in more than one plane, a flat array with n elements per row and m elements per column would require $n \cdot m$ phase shifters, or approximately 320,000 phase shifters and radiators for a 60-db antenna gain.

Combining the phase shifter and the radiator, the Naval Research Laboratory[28] has shown that rotating spiral antenna elements will produce flat arrays capable of beam-scanning with circularly or linearly (variably) polarized patterns. Such arrays can be fed by a horn or point source, like a lens, as well as by a transmission line.

The problem of scanning a rectangular planar array is simplified by using phase shifters only along columns (thus requiring only n, instead of $n \cdot m$, phase shifters). The El Campo, Texas, solar radar (Fig. 14) exemplifies this approach. This giant antenna is scanned in the east-west plane by phase shifters, and in the north-south plane by manual change of the phase to each dipole radiator.

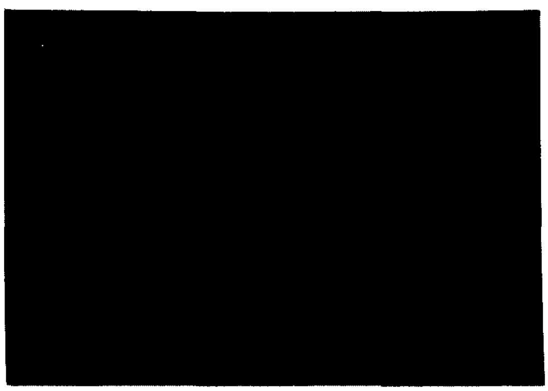


FIG. 14. The El Campo Array for Solar Radar
(MIT Lincoln Laboratory)

Dipoles can be excited simply by proximity-coupling them to a two-wire line. With physical or conductor contact between the dipole radiator and the feeding line thus eliminated, the problem of controlled radiation is reduced to its essentials. Except for devising a means of support for the conductors and providing protection against the weather, all that is required to build a linear array is two-wire line, dipole rods, and proper geometry. Controlled radiation from a transmission line[29] alone, without dipoles, has been achieved with some success. While the ultimate in simplicity is desirable, simplicity can be carried to extremes; all heaps of metal radiate, and a good antenna is not always the simplest but one that we understand and can easily control.

Among the flat arrays, the proximity-coupled dipole can be scanned over 50° from the normal to the array by motion along the two-wire feeder.[11] Feeding from both ends of the array for transmission and reception yields a ± 50° scan angle. Dual-terminal feeding,[30] with corporate-structure phase shifters along the columns and a movable feed on the rows, allows very large arrays to be scanned in a large sector of solid-angle coverage. The dipoles are transported either by relay-controlled trolleys or on a rubber belt (Fig. 8). Such antennas are contenders for a role in the space era because their power-handling, pattern quality, gain, bandwidth, and scan rates are all acceptable for, say, satellite communication in the 50- to 500-Mcps band. Cross or variable polarization is not however possible.

2.7. Interferometers

There is a class of big antennas whose overall dimensions are very large but whose apertures are not completely filled with radiating elements. Such an antenna is usually designed more for angular resolution than for antenna gain, the beamwidth being related to the overall dimension of the antenna array in the plane in which the beamwidth is measured, and the gain being proportional to the number of radiating elements in the array (assuming uniform distribution of power to the elements). The virtues of high-gain-aperture antennas and high-resolving interferometers can to some extent be obtained in one system by separating two large-aperture antennas a long distance apart and producing a fine interferometer lobe structure within the broader beams of the aperture antennas. This technique is being used by California Institute of Technology at Big Pine, Calif., and by the Royal Radar Establishment at Great Malvern, England (Fig. 15). Interferometers are sometimes comprised of many moderately sized apertures widely equispaced to produce many grating lobes. This approach is being used for radio astronomy and solar investigations by Stanford University[31] (Fig. 16) and by the Meudon Observatory in France.[32]

A number of ingenious methods have been advanced for producing a single unambiguous beam from the multilobe patterns characteristic of interferometers. Realizable only on the receiving patterns, the desired effect usually involves some nonlinear operation on the signals. Walsh and Band[33] achieved one main beam by multiplying together the two interference patterns produced by interlaced gratings of different spacings (Fig. 17), obtained with an array of radiating elements much more widely spaced than $\lambda/2$. The pattern is electronically steerable in azimuth

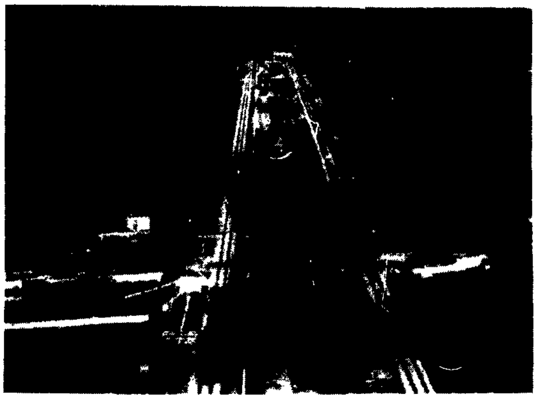


FIG. 15. Radio Interferometer Using Twin 25-meter Paraboloidal Reflectors (Royal Radar Establishment, Great Malvern, England)

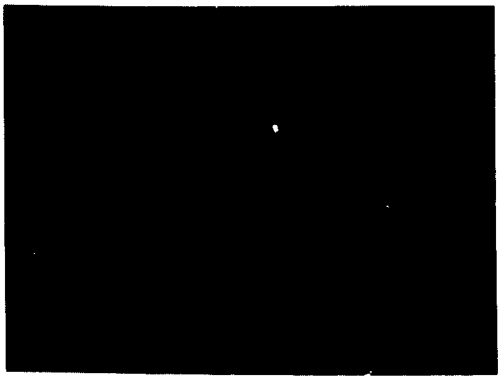


FIG. 16. Stanford University Interferometer for Solar Radio

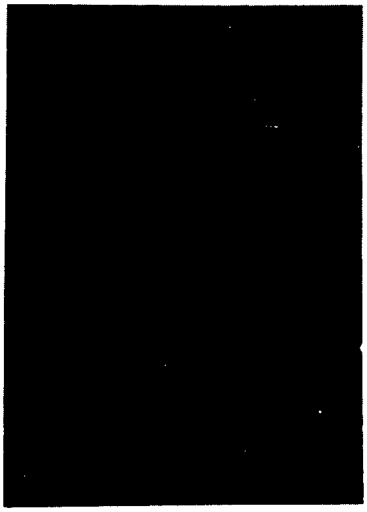


FIG. 17. A 3500-ft Nonuniformly Spaced Electronically Steerable Antenna Array Producing Multilobes (Pickard and Burns)

and the condition for nonambiguous pattern is maintained over a large bandwidth. The Drane-Davenport[34, 35] antenna, a further development of the Covington and Broten array, is also a linear array of nonuniformly spaced elements producing a single antenna beam (Fig. 18). This interferometer is made up of a continuous

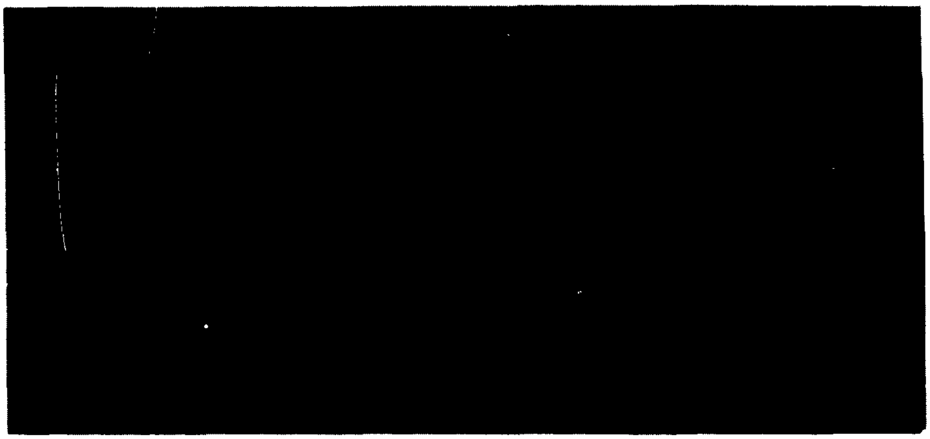


FIG. 18. Drane-Davenport Interferometer Using Nonlinear Processing of Received Signals

section of $\lambda/2$-spaced elements augmented by a regular progression of widely separated radiators. The signals received by these radiators are phase-modulated, correlated, and then multiplied together to produce a single beam. Gabriel of Stanford Research Institute[36] has devised another successful geometric arrangement for a single-beam widely spaced interferometer. With additional nonlinear operation on the signals, it has given extremely good sidelobe control. Workers at Hughes Aircraft[37] have through time-modulation and nonlinear processing succeeded in getting beam-scanning; multilobe generation, and pattern control, among other desirable effects.

The interrelation between antenna pattern and bandwidth of signals received has been shown in a comprehensive inhouse study[38] at RADC. When the spectrum and modulation of the radiated signal can be controlled, as with a radar system, antenna patterns can be significantly controlled by interferometer configuration and signal modulation.

There is much to be said for some exceedingly wonderful results already achieved through research activities in nonlinear antennas[39] but the general usefulness of such antennas is not yet apparent. Nonlinear antennas produce cross products that can distort the information or target image when several coherent or partially coherent signals are received by the antenna. These antennas often lack gain, and signal-to-noise levels are not always improved by the multiplication and correlation necessary to produce the antenna patterns. When interferometer elements are spaced too far apart, random variations in the atmosphere or ionosphere may reduce the 'seeing,' as on large optical telescopes. (Large-aperture antennas are of course also thus affected.) There is a dearth of reliable data on the effects of the medium at various frequencies, but it is reasonable to conjecture that for angles near the earth's horizon the performance of some antennas is degraded by lack of coherence across the large antenna dimension. The performance of linear and nonlinear antennas under conditions of partial coherence has been reported on by Parrent, Skinner, Shore, and Drane.[40-42]

3. ELECTRONIC BEAM-SCANNING

3.1 Voltage- and Current-controlled Phase Shifters

Replacement of mechanical phase shifters in planar arrays by current- or voltage-controlled phase shifters offers the use of inertialess components as the most obvious way of speeding up scanning. The efforts expended on ferrite phase shifters have not yet produced completely reliable, temperature-insensitive, inexpensive components. The work on voltage-controlled ferroelectric devices has been less extensive. In one of the first successful voltage-controlled scanning arrays,[43] varactor diodes served as voltage-controlled phase shifters (Fig. 19).

FIG. 19. Voltage-controlled Scanning Array

With research continuing on materials for electronic phase-control in the transmission lines or guides feeding antenna arrays, a large array carrying high rf power may some day be scanned with low loss by simple voltage variation on the feed lines through low-loss temperature-stable solid-state components.

3.2 Frequency-Scanning

As the frequency on a traveling-wave linear array is varied, the relative phase between elements changes, causing the beam to squint slightly. A nuisance effect on many arrays, the squint can be made the basis for electronic beam-scanning if it is intensified through design so that liberal beam swings are achieved with slight changes in frequency. Such arrays and their feeding lines are dispersive, separating different frequencies into different beam directions much as a dispersive glass prism separates the colors (frequencies) in white light.* Frequency-scanned arrays are feasible with waveguide prisms but it is usually simpler to produce dispersion by means of another nuisance effect—the long-line effect. Long equal lengths of transmission line connecting adjacent radiating elements allow very satisfactory beam-scanning, with tolerable transmission losses. (Obviously, multilobing could be generated by using filters or duplexers to separate the wide spectrum of a received signal, but designers have so far concentrated on instantaneous beam-scanning and pointing accuracy.†)

The main disadvantage in frequency-scanning is that it requires transmission or reception of a wide spectrum. This can be overcome by using long-line dispersion to produce phase shifts; with two mixing operations to generate the proper increments of phase shift between radiators, there is no change in the radiated frequency external to the antenna. The basic idea[44] is that since phase is preserved on mixing, a control signal can be changed in frequency, run through different lengths of dispersive line, and then by a further mixing operation reconverted into the original transmitted frequency but shifted in phase. This method of electronic scanning requires frequency stability for accurate control of the beam position.

The cw control frequencies (sine waves) can be distributed around a large antenna system, with good fidelity even in the presence of noise. This method of beam-scanning requires crystal mixers or other nonlinear elements, which add to the losses of the dispersive lines, so the antenna is no longer reciprocal. The received and transmitted beams must now be scanned separately—but this separation of the transmitting and receiving functions provides an opportunity for generating high transmission power by using a power amplifier with each radiator element while continuing to scan the receiving pattern the same as before. This added versatility, including self-adapting capabilities and design flexibility (Fig. 20), is obtained at a high cost per unit area of antenna aperture.

*C.J. Sletten, P. Blacksmith, Jr., F.S. Holt, and J.E. Holland, Line Source Antenna Arrays for Control of Pattern, Dispersion, and Phase, Technical Memo CRRD-87, 25 February 1963.

† L.A. Gustafson, Unpublished Tech. Memo 462, S-Band Two-Dimensional Slot Array, Hughes Aircraft Co., March 1957.

FIG. 20. Adaptive Antenna Array of Unequally Spaced Horns Covering a 100λ Aperture. This array is capable of automatically radiating the conjugate of a received wavefront to produce a focus at the distant source. It was developed by Research Division, Electronic Communications, Inc., under contract with USAF Rome Air Development Center.

3.3 Incremental Frequency-Scanning

The merits of incremental frequency-scanning were recognized some time ago by Dr. Roy C. Spencer* when he was with AFCRL, but this distinctly different kind of scanning has only recently been appreciated and developed. To scan a phased array, the plane wavefront from the antenna is tilted by linearly increasing (or decreasing) the phase along the array. When this is done at a uniform rate the phase at each element changes at a uniform rate. For example, in $E_n = A_n \sin(\omega t + \phi)$, let $\phi = n \Delta f t$. Then $E_n = A_n \sin(\omega + n \Delta f) t$. Thus, a phased array can be made to scan at a uniform rate if the frequency at each consecutive radiator is increased by an amount Δf.

Cottony of the National Bureau of Standards has succeeded in producing the harmonics Δf, $2\Delta f$, $3\Delta f, \ldots,$ $N\Delta f$ (where f is proportional to the scan rate) and adding them to a higher rf frequency. Since f and its family of harmonics can be varied, the beam can be made to vary in sweep speed. Cottony[45] has obtained a rapid beam sweep by using the $N\Delta f$ technique to modulate the local oscillators on the receivers attached to Yagi antennas (Fig. 21). If the elemental radiators are directional there is some 'dead time' when the beam is scanned in directions where the elements have little gain. The radiated spectrum required is no greater than that for any rapid scanning method.

*Rapid Scanning by Adjustable Frequency Transmitters, first in a series of five WLCAL memorandums beginning 21 July 1947

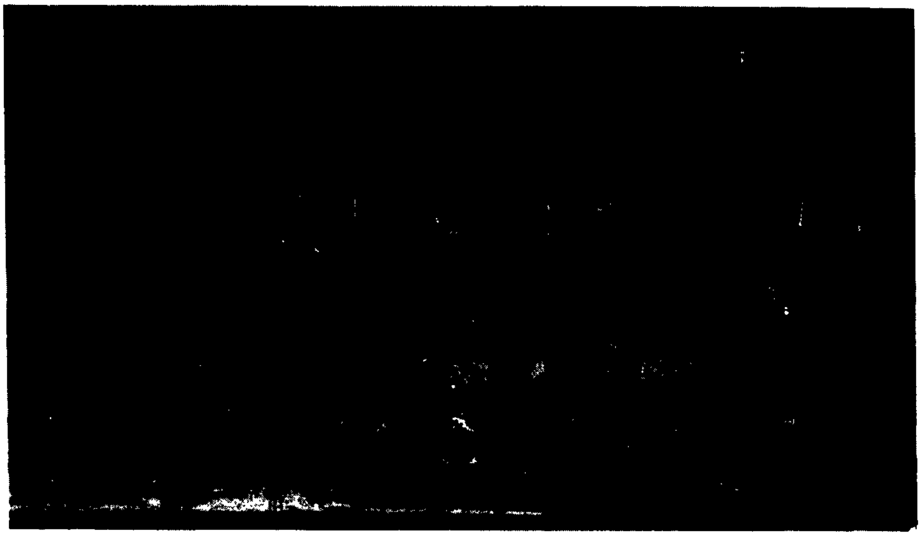


FIG. 21. A High-resolution Antenna Array Electronically Scanned by Incremental (Δf) Method (Boulder Laboratories, National Bureau of Standards)

3.4 Amplitude-Scanning

The methods discussed so far for electronic beam-scanning from a fixed array or aperture all depend on producing a variable phase at the radiating elements while keeping the amplitude or power at each radiator as constant as possible.

Electronic beam-scanning can also be done by keeping the phase fixed, and varying the relative amplitude[46] to the radiators from + 1 to - 1. This approach has certain advantages. The output of a balance amplifier can be conveniently varied from + 1 to - 1 by changing grid voltages only. Such scanning methods can be adapted to circular arrays (r, θ geometry) not adequately steered by the equiphased elements developed by dispersive methods. (Circular arrays can of course be electronically scanned by phasing methods.) Mutual-coupling effects can be reduced in scanning circular arrays and, with more difficulty, in scanning linear or mattress arrays. Schell[47,48] has shown that concentric loops and corner reflectors (Fig. 22) can be amplitude-scanned. The University of Tennessee[49] has obtained excellent sidelobes on electronically amplitude-scanned circular arrays (Fig. 23).

The disadvantages of amplitude-scanned arrays are: (1) the radiators required are usually more than for equivalent phased arrays, and (2) each amplifier is not

FIG. 22. Scannable Corner Reflector

FIG. 23. Amplitude-scanned Circular Array of Concentric Monopoles Over a Ground Plane (University of Tennessee, Knoxville, Tenn.)

used at full output at all times. The suggestion that one half of the radiators could be dispensed with if all amplifier outputs were combined in a junction to produce a variable phase output is not valid. Such a junction would have intolerable reflection (impedance) characteristics, and its use would mean giving up the advantage of being able to add the amplifier outputs in space. As for the objection that each amplifier is not fully utilized—under rapid-scan conditions each tube can be used to its full plate dissipation, and a common power supply used to its maximum rating. The advantages of amplitude-scanning and its related synthesis method certainly outweigh its disadvantages, and the technique is yet to be fully exploited.[50]

4. REFLECTOR ANTENNAS AND FOCAL REGION RESEARCH

4.1 Reflector Efficiency

Most reflector antennas have an efficiency of about 50 percent. This represents a 3-db loss in gain, which leaves the antenna gain equivalent to that of an ideal aperture only one-half the size. The loss is principally spillover—energy that escapes striking the reflector because the optical method of feeding such reflectors spills it over the rim. Such losses cannot be prevented by making directive feeds larger because the implicit severe amplitude tapering would itself cause a drop in gain. Spillover energy usually intercepts the warm lossy earth and adversely affects the noise temperature of the antenna.

No one has yet derived a cheaper and more satisfactory large-aperture antenna than by using a single metal reflector surface. The larger the reflector and the sharper its beam, however, the greater its optical aberrations—and the closer the area of operation shrinks to the focus. The antenna structure becomes harder to move, and phase coherence becomes harder to maintain during scanning motion. Although the gain and angular resolution remain phenomenally good, the search or surveillance capability becomes poor. With the focal point and reflector in motion, it becomes harder to ascertain the angular coordinates of the beam when target acquisition is made. The distant target eludes the needle beam altogether.

4.2 Reflector Capability

The optical reflector gets its wide-angle capability from its long focal length, usually three to five times the aperture width. Antennas usually have an f/D of 1/4 to 1/2 since long focal lengths on fixed reflectors structurally require extremely tall towers. Kraus's[6] radio telescope, however, with its focal axis on a metalized ground plane, is a design that allows taking advantage of the magnification and improved wide-angle performance provided by a long focal length. For the spherical mirror, Spencer[17] suggested the longitudinal corrector, having found that a microwave radial line source for a spherical reflector can be phased to correct for spherical aberration, thus allowing aberrationless scanning of a pencil beam over a large solid angle.

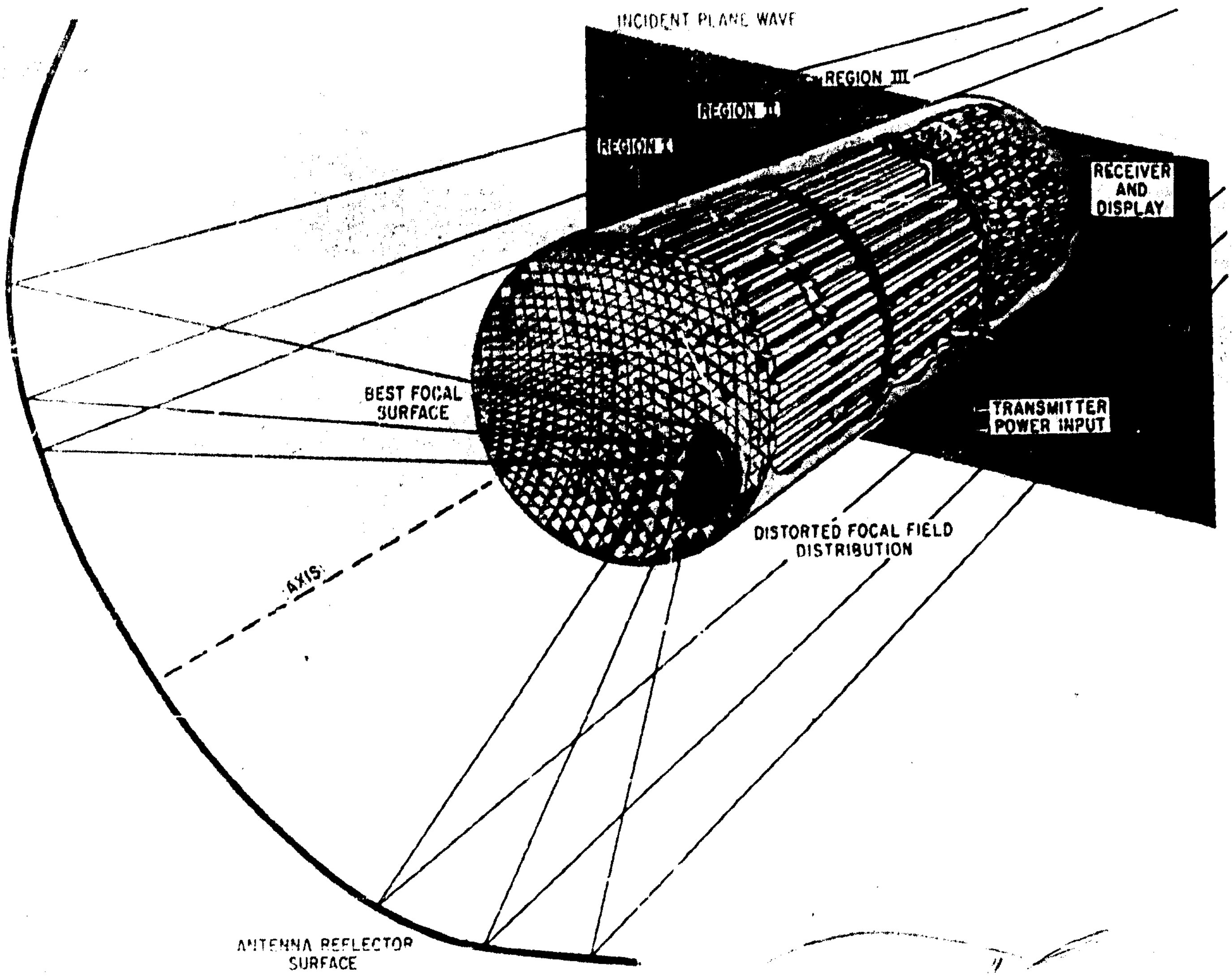
It has been possible to correct optical errors in the paraboloidal antenna to some degree by calculating the position of high-intensity ridge lines and placing phased line sources along these curved longitudinally extending surfaces.[51] Since, unlike that of the spherical reflector, the caustic surface of the paraboloid does not degenerate into lines, the correcting line sources do not eliminate all optical errors. They do markedly improve patterns at wide angles from the axis direction, but each beam direction requires a different length of phased corrector.

Optical designs suitable for incoherent light do not hold the complete answer to giving space antennas the angular acuity and information-rate capability of the human eye or the optical telescope. In radio it is possible to control the phase, amplitude, and polarization of the fields in the focal region down to detail areas about $(3\lambda/4)^2$ in size. Since the focal energy distribution is a Fourier transform of the incident (or desired) energy distribution on the reflector aperture, the focal energy can be selectively rephased and collected to correspond to a desired inphase amplitude-tapered aperture distribution that will in turn produce the required far-field patterns. The question is: Can the energy spread and phase distortion in the transverse focal region be processed out to approximate on-axis quality in the antenna patterns for off-axis directions? The experimental answer is to date a qualified yes.

Sidelobe levels over both wide angles and wide frequency bands have been remarkably reduced by inserting auxiliary feeds in the focal regions according to the location of the field distributions.[52,53] These transverse correctors—compensating feed structures transverse to the axis of the reflector or in the focal plane—offer great advantages, but no ambitious twin-pronged theoretical and experimental attack has as yet been launched against the problem of restoring gain and reducing objectionable sidelobes of highly aberrated antennas. I predict such a program would succeed. The sequence of processing operations and the benefits to be obtained are indicated in Fig. 24.

4.3 Nature of the Focal Region

A circular aperture with a uniform amplitude distribution focused into a converging spherical wavefront produces a field distribution described approximately by the Bessel function $[J_1(x)]/x$. It should follow then that the cone of energy



REGION	OPERATIONS	FUNCTIONS
I	PASSIVE, LINEAR, FIXED-GEOMETRY PROCESSING PERFORMED BY INTERCOUPLED NETWORKS THAT CONNECT ELEMENTAL FEEDS LOCATED ON BEST FOCAL SURFACE	RESTORE PATTERN TO ON-AXIS FOCAL QUALITY CONTROL APERTURE ILLUMINATION AND SPILLOVER
II	PASSIVE, LINEAR, ELECTRONIC SWITCHING	INTERCONNECT BEAMS FOR BEST SCANNING AND SEARCH PATTERNS (THROUGH VARIABLE NETWORKS AND SWITCHES) ADJUST PHASING CHANNELS TO PERMIT FOCUSING IN NEAR ZONE OF ANTENNA APERTURE
III	ELECTRONIC NONLINEAR PROCESSING (MIXING AND AMPLIFICATION)	COMPARE PHASE FOR EXTRACTING ANGLE DATA FROM WIDE ANTENNA BEAMS COMPARE MONOPULSE FOR ACCURATE TRACKING OPTIMIZE RECEIVED PATTERNS (DEPENDING ON TARGET CHARACTERISTICS) CONTROL AUTOMATIC AND SELF-ADAPTING TECHNIQUES

Fig. 24. Operations and Functions Performed in Focal Region Processing

produced by a feed structure exciting (or receiving) a field distribution $[J_1(x)]/x$ will illuminate the aperture in a uniform plane wave. The fact is that the $[J_1(x)]/x$ distribution in the focal region is infinite in extent, and spillover cannot be entirely eliminated. By judicious use of Fourier transforms and optical methods, effective transverse feed structures can be designed to give improved aperture efficiency, spillover reduction, and optimum relations between sidelobes and gain.

In usual engineering practice the Fourier transform description of focal fields is not used. Antennas are designed according to microwave optics principles, the assumption being that antennas focus energy to a 'point' in the focal plane where it is received (or transmitted) by a point source. Radiating points are of course always extended in the form of horns, dipole arrays, or other small apertures. The radiation patterns of these feeding structures are said to determine the taper (amplitude distribution) across the big lens or reflector, as well as the spillover (energy that misses the secondary aperture altogether).

This is a rather sketchy description of the effects of the primary feed and secondary aperture cooperating to produce a radiation pattern. If we examine the characteristics of the aperture (usually a paraboloid or lens) apart from the effects of the feed structure, two main facts appear.

First, with a uniform plane wave incident on a perfectly focusing circular aperture (distortionless in phase, amplitude, and polarization), the focused energy is distributed in the so-called Airy disk and ring structure.[54] The disk receives over 80 percent of the energy falling on the aperture. The rest falls principally in the inner concentric rings whose widths are approximately equal to the radius of the disk. The phase of the focused energy is uniform throughout the disk or throughout any ring but takes a <u>180° jump</u> between adjacent rings and between the inmost ring and the disk. If the incident plane wave (flat-phase wave) varies in amplitude—for example, if the incident energy is concentrated at the center of the antenna aperture and attenuated at the edges (tapered)—the disk widens out and receives a larger percentage of the energy incident on the reflector.

Second, the disk and ring structure changes size approximately linearly with the focal length: the longer the focal length, the larger the radius of the Airy disk and rings.

The main function of the primary feed is to collect (absorb) the focused energy (By the reciprocity principle in optics, the transmitting and receiving patterns of an aperture antenna are the same.) The designer's efforts are usually limited to devising small radiators that are about the size and shape of the Airy disk and correspond to a slight amplitude taper and <u>linear</u> phase front determined from incident wave analysis.

A horn fits nicely over an Airy disk unless the designer forgets that the horn must have a flat phase front and a taper matching those of the disk. If the horn is too large the phase front is often no longer flat and the amplitude, particularly in the E plane, is not sufficiently tapered. The resulting Airy disk and ring structure is as though produced by an incident plane wave, with phase errors in the radiation pattern discernible by filled nulls and loss in gain. The amount of tapering that can be achieved by increasing the directivity of the primary feed thus has a practical limit.

The usual flared horn that projects out of the focal plane raises another problem: unless the energy on the edge of the horn is very low the rim acts as a source far out of focus. Since short-focus antennas have very small focal regions, flaring and extending the horn to fit the wide cone angle needed to feed such flat systems can have adverse effects.

4.4 Advantages of Focal Region Research

Improved reflector aperture efficiency (in effect increasing the size of the antenna), reduced spillover injection of thermal noise into the antenna, and multilobe systems of good beam quality and high information rates can all result from focal region research.

To speculate a little on how future antennas will look and operate, let us consider the Lincoln Laboratory 60- and 120-ft X-band antennas. The 120-ft antenna under construction is pressing the limit of mechanical tolerances that available materials will allow. The shortest radio waves that are not seriously attenuated by the earth's atmosphere are about 3 cm. This antenna appears to be approaching some fairly fundamental limits for space exploration and surveillance. Although a very advanced design now, it may become simply typical as we progress into the space era. Figure 25 shows the present feed for the 60-ft reflector. The antenna has a beamwidth of about 0.057°, and through a very ingenious 12-horn feed system[55] produces a multilobe pattern. Monopulse comparison of the multibeams enhances the angular pointing accuracy to seconds of arc while providing a constant full-gain beam in the center of four other beams used for accurate tracking. Another feature of this antenna is the auxiliary Cassegrain reflector that allows the focal region to be folded back to the vertex region of the large paraboloidal surface. The great convenience afforded by a primary feed structure embedded in the curved ground plane over the axis of the pedestal costs a bit in increased aperture-blocking and rather minor spurious lobes caused by diffraction and spillover from the Cassegrain system, but this cost is partially offset by the advantage that the focal region is magnified much as in a long-focus optical telescope. The wide-angle characteristics of the antenna system are not necessarily better or worse than without the Cassegrain.

Consider the class of high-gain, narrow-beam microwave antennas typified by the 60-ft and 120-ft 3-cm antennas. How can focal region engineering produce a large cluster of high-quality multibeams for search and rapid gathering of, say, radio astronomy data, and at the same time improve the aperture efficiency and noise temperature of the antenna by reducing spillover? The multihorn feed could be used for more than beam comparison alone. The number of elementary horns ($3\lambda/4$ by $3\lambda/4$) could be increased to populate as large a region as shadowing (aperture-blocking) effects permit. To form good off-axis antenna patterns, the output of a number of these elementary horns could be coupled and phased together according to knowledge of the focal field distributions provided by Fourier transform calculations. With regular and slowly varying phase errors, passive

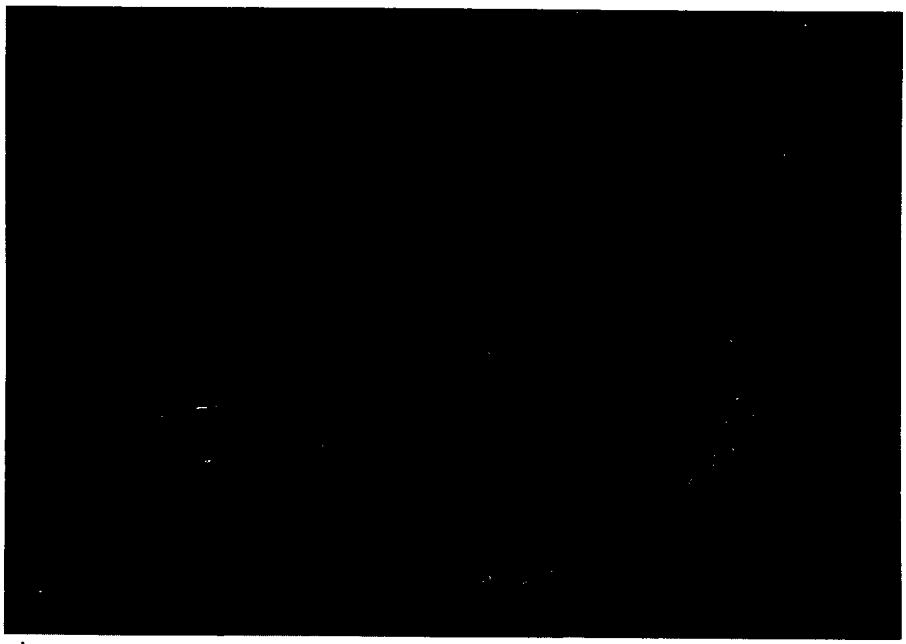


FIG. 25. Twelve-Horn Monopulse Primary Feed for MIT Lincoln Laboratory 60-ft Paraboloid

coupling by (for example) directional couplers to adjacent waveguides feeding the elementary horns should succeed in transforming the horn inputs to a set of output terminals with the desired cluster of overlapping beams. To equalize the intercoupling of feed lines or guides for all areas of the focal plane, the Cassegrain folding system might be designed to equalize the phase errors over the focal region rather than to focus perfectly on-axis. The Cassegrain design offers another advantage in that magnification of the focal regions allows more room for waveguides and directional couplers behind the feed horns and the main reflector.

Once the beam is successfully reconstituted by focal plane transformation, we will want to be able to control the variables in these processes. For objects in the near zone of the antenna, rapid focusing is important. Sidelobe levels may have to be increased to improve gain and angular resolution, depending on the spatial frequency of the target of interest. It is quite obvious that once high-gain beams are formed, signals can be amplified above detector noise for scanning and fanbeam formation. It is conceivable that aberrations can be corrected and beams efficiently focused by first detecting and amplifying and then electronically phasing and coupling at more convenient frequencies. For transmitting antennas it is important to preserve the inherent linear passive characteristics. The focal region processing should therefore be accomplished before amplification or other nonlinear operations.

Although focusing antennas affording multiterminal operation are not new, their usefulness in conjunction with the costly high-gain antenna for space applications is clear. The capabilities of large-aperture reflector surfaces, with or without auxiliary reflectors, can be enhanced through knowledge of their electromagnetic field structure in the focal region and improved signal-processing techniques.

5. PROPERTIES OF TYPICAL ANTENNAS

The information an antenna can gather from radiating sources depends on bandwidth, operating frequency, pattern characteristics, antenna gain, and number of antenna ports or terminals. There being no logic in amassing extraneous information, the paramount objective in designing an antenna is to fit it for its special functions and the anticipated characteristics of sources or targets

5.1 Circular Arrays

A circular array (Wullenweber type of antenna) is the natural configuration for scanning the horizon. The antenna designed by Andrew Alford Consulting Engineers,[56] Boston, Mass. (Figs. 26), covers the frequency band from 225 to 400 Mcps and produces rapid 360° scan by rotation of its miniaturized commutator. Proper phase and amplitude to any 90° sector of wideband dipoles is maintained through broadband transmission line techniques.

5.2 The Luneburg Lens

The geodesic principle (Fermat's principle in optics) that electromagnetic waves will follow a minimum path over a surface or through a medium is basic to the Luneburg lens.[57] Both circular and spherical coordinate systems can be scanned by points moving around the periphery of a disk or sphere whose index of refraction $\underline{n}$ varies with the radius $\underline{r}$ according to $n = \sqrt{2-r^2}$, $r \leq 1$.

The Rinehart-Luneburg lens shown in Fig. 27 shows how such an antenna can be constructed with shaped parallel plates. Radiators placed around

FIG. 26a. Experimental Fixed Circular Array

FIG. 26b. VHF/UHF Noncontacting Delay Line Type of Scanner for Wullenwebber (internal view)

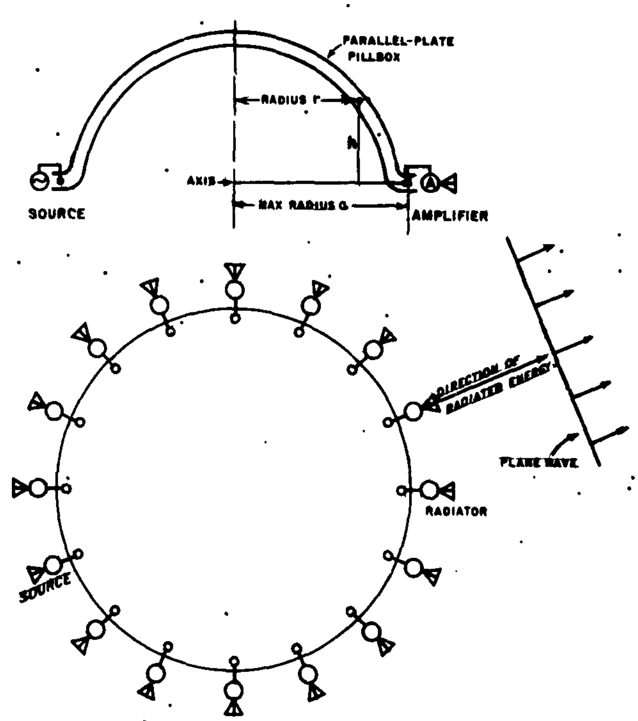


FIG. 27. Electronically Scanned Circular Array Using Rinehart-Luneburg Lens Constructed of Shaped Parallel Plates for Beam Formation. Active elements on the focusing Luneburg lens function as amplifier or oscillator sources, depending on dc bias. When one element is selected as a source and its output coupled into the lens pillbox, the other elements (amplifiers) will be fed by the pillbox probes and their outputs will be properly phased to direct a plane wave in the direction shown.

the rim of the lens act as amplifiers or as point sources that illuminate, in proper phase, the amplifiers in the opposite sector of the lens. Such lenses are very broadband. Scanning and multilobe operations can be achieved with suitable feeding systems

5.3 The MUBIS Antenna

Another wide-angle lens system provides multilobe coverage, each beam scanning an interval or angular sector. The essential ideas in the MUBIS[58] antenna are shown in Fig. 28. Wide-angle lens performance is obtained by means of a special shaped parallel-plate region and a type of constrained lens called the "Bootlace Aerial" by its designer, Gent of the Royal Radar Establishment at Malvern, England. A constrained lens is one in which incident energy moves through the lens region in paths directed by waveguide or transmission lines rather than according to Fermat's principle as in most optical lenses. Such lenses[59] allow more freedom of design than dielectric lenses, and very wide angles can be covered with short focal lengths (f/D small). These lenses and many forms of geodesic lenses were investigated shortly after World War II. In spite of their high cost and complexity, they have found many applications.

FIG. 28. Multiple Beam Interval Scanner (MUBIS)

5.4 Multibeam Arrays

In some multibeam, multiport linear arrays, the received rf energy at each radiator is amplified and mixed with phased cw local oscillator signals to a convenient intermediate frequency. These mixed signals are fed into a symmetric multiport matrix of lumped transmission line elements. Simultaneous antenna beams are possible in all available "look directions" from the array.

Efficient multiport linear arrays for microwave frequencies can be constructed by using linear passive components. A waveguide matrix interconnected with directional couplers gave Blass of the Maxson Corp.[60] an excellent multilobe array that can be used either for reception or transmission. Combinations of hybrid couplers have been used by other workers[61] to extend rf multiport techniques to circular arrays. .

5.5 Reflector Antennas

Among methods available for obtaining more information from focusing (optical) systems, schemes for improving the multilobe-gathering ability of single-surface reflector systems deserve particular attention.

Focusing antennas can be used to produce shaped beams by extending the feed source or sources across the focal plane.[51] It is convenient to form a $\csc^2\theta$ pattern (θ = elevation angle) by extending the feed source along a line of sharp azimuth focus, and by using a portion of the paraboloid reflector surface above the vertex, an off-axis or no-aperture-blocking solution can be obtained. It turns out that the proper location for the feed is along a straight line passing through the focus parallel to a tangent to the midpoint of the paraboloidal section (Fig. 29). Although positioning the line source below the focus results in low aperture-blocking and improved impedance characteristics, extending the feed sources in a line in front of the reflector aperture gives better patterns from each source.

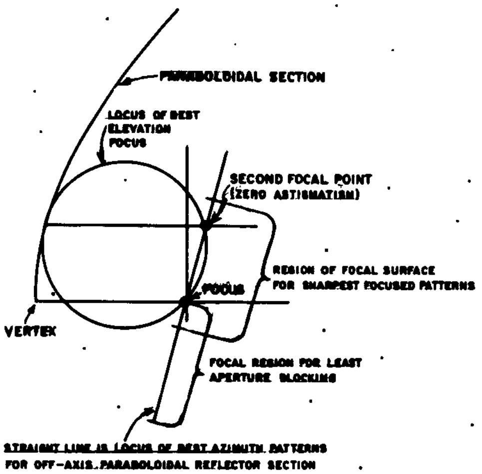


FIG. 29. Best Focusing Loci for Wide-angle Antenna Patterns From a Paraboloid

An off-axis section of a paraboloid has two focal points: a true focus, and a zero astigmatism focus. By working in the proper focal region, good antenna patterns can be obtained over a 60° sector. Radiating elements such as slots in a waveguide must be phased with respect to one another so as to focus the array energy at the midpoint of the reflector section. Because of the rotational symmetry of the paraboloid, two or more beams can be rotated about the focus to form V beams in space from a single reflector.[62] By noting the elapsed time of target passage through the V beams, it is easy to obtain the height or elevation angle of the target from an antenna rotating only in azimuth.

These V beams are shaped by feeding the appropriate power to elemental radiators in the focal region of a focusing lens or reflector. The image of the object distribution is formed at infinity or, practically speaking, in the farfield of the antenna. In optical systems the relative phase of sources in the focal region is usually not controllable on a point-to-point basis; on a paraboloid, beamshaping is best accomplished by focusing (phasing) the line source toward a central spot on the reflector. With certain wide-angle lenses and reflectors like the sphere or parabolic torus, this focusing or phasing relation between feeding radiators can be relaxed and good patterns still produced. Under these conditions the relative phase between sources in the focal region can be used to control the antenna phase-pattern in space. Control can be achieved by connecting together a row (or any regular configuration) of point sources in the focal region by a traveling-wave feed line with terminals at each end. Since the signal received by a given point source (given beam direction) will arrive at each terminal of the feeding line with a different phase, the angular direction of an arriving plane wave received by a broad shaped pattern can be measured with considerable accuracy. If the point source radiators are progressively phased δ degrees apart, the change in relative phase between the two terminals will be 2δ degrees as the plane-wave angle of incidence focuses from one point source to an adjacent point source; Fig. 30 illustrates such

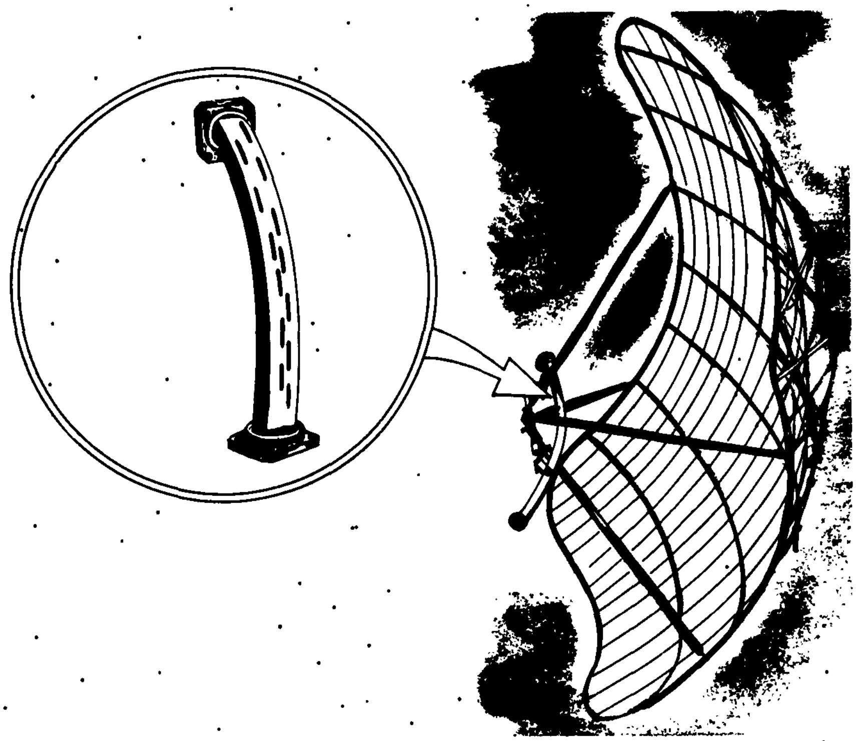


FIG. 30. Curved Line Source Feed and Parabolic Torus Reflector for Tricoordinate Radar Antenna. Angular position is obtained from phase in space.

an antenna operating as a radar. The antenna phase-pattern has not been used very much yet it provides an important additional source of data when phase comparisons can be easily made. Phase can be varied rapidly without changing the antenna pattern whereas amplitude comparisons depend on changes in the antenna gain as a function of angle.

5.6 General Considerations

Before going on to discuss some new antenna research, a few general remarks on enhancing the information content of antennas will bear repeating.

It is usually better to operate radiating systems at lower frequencies than high (Fig. 3) since the receiving cross section of a dipole antenna varies with λ^2.

The simplest antenna that gathers the needed systems data with sufficient gain and angular accuracy is the most desirable—a truism seldom helpful to the designer. But the antenna that selfadapts to signal sources is not just a dream in this age of automation (Fig. 20). Signals with slowly varying phase fluctuations can be phased together to realize a large coherent aperture. By spatial frequency techniques, antennas can be made to adjust their amplitude taper for better resolution of the targets being mapped.

6. SOME IMPORTANT UNSOLVED THEORETICAL AND ENGINEERING ANTENNA PROBLEMS

There are many interesting and worthwhile problems in antenna design still unsolved. I have already gone into detail on the technical approaches in several of what I consider the most important and useful areas of applied research. I wish to discuss a few antenna problems that deserve treatment when fresh insight and ideas for their solution are available.

6.1 Antenna Pattern Synthesis

There is hardly a study more fundamental to antenna design than one encompassing theoretical and experimental approaches to producing a given radiation pattern in space or other media with a prescribed organization of radiating sources. A great many specialized synthesis techniques are available: ray optics for shaping metal reflectors to form patterns, Fourier transform methods for calculating a continuous aperture distribution, Fourier series and Tschebyschev polynomial methods for finding optimum feeding coefficients on arrays of discrete radiators, and many mathematical refinements of these synthesis methods. In spite of many good endeavors,[63-65] tractable methods for optimally synthesizing a given power are still lacking. To produce a given power pattern in space we are usually willing to let the antenna phase-pattern in space be unprescribed if this will allow us to approximate a desired pattern more closely with a given number of radiating elements or a given aperture size. When only the power pattern is specified, there is no longer a unique solution to the best feeding coefficients in a given aperture. Besides finding the closest approximation to a desired pattern in some sense (like minimizing mean square errors) the designer seeks a realizable aperture distribution with smooth variation in the excitation field between radiators or neighboring points in the aperture.

Several other neglected synthesis problems should be tackled. What about synthesizing a phase-pattern in space with a smooth but unspecified amplitude pattern? This problem needs solution so that the available relative phase functions on dual- or multiple-terminal arrays can be known. Another ignored problem is that of synthesizing an arbitrary solid-angle radiation pattern. A good optical technique is required for shaping a doubly curved reflector to produce search patterns in a solid-angle sector but a satisfactory answer has not been found.

Synthesis from sources arranged with random spacing, nonuniform spacing, and almost periodic spacing, has received some attention in recent years.[63] More cooperative work on mathematical analysis, machine computation, and antenna engineering, may continue the thinning-out of the vast population of radiator elements and furnish better ways of producing suitable coverage patterns and sidelobe levels.

6.2 Supergain Antennas

Several advances[66] in supergain synthesis have been made. In spite of the difficulty of maintaining control over large reactive currents and storage fields, modestly superdirective arrays with a limited number of elements may have important practical applications for, say, low-frequency directive antennas, endfire arrays, and microwave arrays composed of superconducting metals. Realization of the tantalizing benefits of supergain will perhaps come from careful study of mutual coupling on closely spaced radiators.[67]

6.3 Boundaries and Modes

Good progress has been made in understanding surface-wave radiation[68] and the modes possible in isotropic unbounded media. But more remains to be done before we can couple and completely control the radiation from slow-wave structures, leaky-wave antennas, stratified media, and other mode-supporting structures. Antennas fed by a combination of surface modes and transmission lines have not been well analyzed. The wideband log-periodic structures also require more theoretical work. Very few rigorous solutions to boundary value problems relating to fed elements about the size of a wavelength are available except for electric dipoles, slots, and loops. We could use a few more building blocks for broadband array design, for example.

6.4 Solid-state Amplifiers

There have been many efforts to combine the antenna with solid-state amplifiers or oscillators.[69, 70] (See Fig. 31.) Schemes for doing this are discussed under phased arrays. Additional improvements in packaging such scanning antennas have been realized by physically placing tunnel-diode amplifiers in radiating slots. Perhaps the most fruitful activity in antenna design today is led by systems engineers who appreciate how to use antenna configuration and nonlinear processes on signals collected from ensembles of these radiators to get and display information vital to a given system.

FIG. 31. Time-modulated Antenna (Hughes Aircraft)

6.5 Partial Coherence

Electromagnetic theory[71, 42] has recently been significantly enlarged to include field (amplitude, phase, polarization) fluctuations in time and space. Studies in partial coherence have been necessary to explain radiation effects from partially coherent laser or other optical sources, and have also helped to explain the behavior of antennas in random fields encountered in tropospheric scatter communications. Further work on the fundamental statistical properties of electromagnetic waves are necessary to aid in engineering better radiation techniques.

6.6 Lossy and Anisotropic Media

Many leading physicists and engineers are working on the subject of antennas surrounded by lossy and anisotropic media[72] to seek answers to radiation blackout problems caused by the plasma sheath that surrounds antennas on missiles reentering the earth's atmosphere and those caused by the conditions of burying antennas under the earth. Although surface-wave theory for lossy stratified dielectric and ferrite media is directly applicable, a number of new problems have emerged.

6.7 Remarks

This survey of antenna research and techniques has concentrated on methods and problems applicable to the electromagnetic spectrums from 1 Mcps to 50 kMcps. Antennas in the kilocycle frequency range, particularly the buried ones, pose special design problems requiring extensive and costly engineering and research. The infrared and optical frequency regions emphasize coherence effects and new transmission modes and demand special lens and reflector designs.

References

1. G.E. MUELLER, A pragmatic approach to space communication, Proc. IRE 48(No. 4):557, Apr. 1960.

2. R.C. HANSEN and R.G. STEPHENSON, Communication at megamile ranges, Microwave J. 4(No. 12):79-85, Dec. 1961.

3. R.N. BRACEWELL, How large can a microwave antenna be? Microwave J. 5(No. 1):57-61, Jan. 1962.

4. N.L. ASHTON, A Feasibility Study for a 300-foot Parabolic Antenna, AFCRL-125, Contract AF19(604)-7349, Mar. 1961.

5. R.M. EMBERSON and N.L. ASHTON, The telescope program for the National Radio Astronomy Observatory at Green Bank, W.Va., Proc. IRE 46(No. 1):23-34, Jan. 1958.

6. J.D. KRAUS, R.T. NASH, and H.C. KO, Some characteristics of the Ohio State University 360-foot radio telescope, IRE Tr. Antennas and Propagation AP-9(No. 1):4-8, Jan. 1961.

7. K.S. KELLEHER and H.H. HIBBS, Feed stabilization system, (U)Proc. 4th Symposium on Scanning Antennas, NRL Rpt No. 4000, pp. 32-40, Naval Res. Lab., Washington, D.C., Apr. 1952. CONFIDENTIAL

8. G.W. SWENSON and Y.T. LO, The University of Illinois radio telescope, IRE Tr. Antennas and Propagation AP-9(No. 1):9-16, Jan. 1961.

9. E.B. CHISHOLM, Antenna for VOLIR, AFCRL Tech. Rpt No. E5062, Dec. 1950.

10. W. ROTMAN and A.A. OLINER, Asymmetrical trough waveguide antennas, IRE Tr. Antennas and Propagation AP-7(No. 2):153, Apr. 1959.

11. C.J. SLETTEN and G.R. FORBES, Broadside, endfire, and scanned beams obtained from arrays of variably spaced elements that are proximity-coupled to a two-wire line, Proc. 6th Communications Scanning Symposium, IRE, Utica, N.Y., Oct. 1960; Broadside and Scanned Beams From Arrays of Variable Spaced Elements Proximity Coupled to a Two-Wire Line, AFCRL-62-727, Sept. 1962.

12. A.C. SCHELL, The Multiple Plate Antenna, Sc.D. thesis, MIT, Aug. 1961; Optimization of Antenna Systems, AFCRL-62-736, Sept. 1962.

13. J.H. PROVENCHER, Experimental Study of a Diffraction Reflector, AFCRC-TR-59-126, Apr. 1959.

14. M.J. KING et al., Quasi-Optical Components and Surface Waveguides for the 100 to 300 kMc Frequency Range, AFCRL-TN-60-1157, Electronic Communications, Inc., Sci. Rpt No. 2, Contract AF19(604)-5475, Nov. 1960.

15. K.S. KELLEHER, Scanning antennas, in Antenna Engineering Handbook, H. Jasik, Ed., McGraw-Hill, 1961, page 15-12.

16. R.C. GUNTER et al., The Mangin Mirror, AFCRC-TR-54-111, Apr. 1955.

17. ROY C. SPENCER, C.J. SLETTEN, and J.E. WALSH, Correction of Spherical Aberration by a Phased Line Source, AFCRC Tech. Rpt No. E5069, May 1951; also, Proc. Ntl Electronics Conf. 5:320-333, 1949.

18. WILEY ELECTRONICS CO., Research Directed Toward Theoretical and Experimental Investigations of Corrected Line Source Feeds, AFCRC-TR-60-122, Final Rpt, Contract AF19(604)-5718, Mar. 1960.

19. W. ROTMAN, The channel guide antenna, Proc. Ntl Electronics Conf. 5:190-202, 1949.

20. A.F. KAY, A Line Source Feed for a Spherical Reflector, AFCRL-529, Contract AF19(604)-5532, May 1961.

21. A.C. SCHELL, The diffraction theory of large-aperture spherical reflector antennas, Paper 11/1, WESCON, San Francisco, 22-25 Aug. 1961; to be published in IRE Tr. Antennas and Propagation, July 1963.

22. E.E. ALTSHULER, Large Spherical Antennas for Aerospace Research, AFCRL-745, Aug. 1961; A Periodic Structure of Cylindrical Posts in a Rectangular Waveguide, AFCRL-175, April 1961 [IRE Tr. MTT MTT-9(No. 5):398, Sept. 1961]; Primary Pattern Measurements of a Line Source Feed for a Spherical Reflector, AFCRL-706, Aug. 1961 [IRE Tr. AP AP-10(No. 2):214, Mar. 1962]; A Monopole Array Driven From a Rectangular Waveguide, AFCRL-62-8, Jan. 1962 [IRE Tr. AP AP-10 (No. 5):558-560, Sept. 1962].

23. A.W. LOVE, Theoretical and Experimental Investigation Leading to Design and Construction of a Broadband Line Source Illuminator, Contract AF19(604)-8385, Wiley Electronics Co., Feb. 1962.

24. F.S. HOLT and E. BOUCHE, A Gregorian Corrector for Spherical Reflectors, AFCRL-62-163, Apr. 1962.

25. C.J. DRANE and G.B. PARRENT, Jr., Selection of Optimum Antenna Arrays, AFCRC-TR-57-109, May 1957.

26. B.Y. MILLS, A.G. LITTLE, K.V. SHERIDAN, and O.B. SLEE, A high resolution radio telescope for use at 3.5m, Proc. IRE 46(No. 1):67-84, Jan. 1958.

27. J. RUZE, An Antenna System for Experimental Long-Range Radar, Tech. Rpt No. E5099, AFCRC-53-24, July 1953.

28. R.M. BROWN, Jr., and R.C. DODSON, Parasitic Spiral Arrays, NRL-5497, AFCRL-TN-60-996, Aug. 1960; IRE Intl Conv. Record (Part 1—Antennas and Propagation) 8:51-56, Mar. 1960.

29. L. HATKIN, An Investigation of a Fast-Wave Radiator, USASRDL-2219, U.S. Army Signal R&D Lab, Apr. 1962.

30. C.J. SLETTEN, G.R. FORBES, Jr., and L.F. SHODIN, Keeping track of earth satellites, Electronics 31(No. 41):81-83, Oct. 1958; C.J. SLETTEN et al., A New Single-Antenna Interferometer System Using Proximity-Coupled Radiators, AFCRC-TR-58-115, Mar. 1958.

31. R.N. BRACEWELL, Interferometry and the spectral sensitivity island diagram, IRE Tr. Antennas and Propagation AP-9(No. 1):59-67, Jan. 1961.

32. E.J. BLUM, J.F. DENISSE, and J.L. STEINBERG, Radio astronomy at the Meudon Observatory, Proc. IRE 46(No. 1):39-43, Jan. 1958.

33. J.E. WALSH and H.E. BAND, Final Report on Interferometer Development, AFCRL-TR-60-120, Contract AF19(604)-4535, Pickard and Burns, Feb. 1960.

34. C.J. DRANE, Jr., Phase-Modulated Antennas, AFCRC-TR-59-138, Apr. 1959.

35. L.C. DAVENPORT and C.J. DRANE, Jr., Correlation antennas with non-uniformly spaced elements for incoherent sources, Paper 11/2, WESCON, San Francisco, 22-25 Aug. 1961.

36. W.F. GABRIEL, Pattern Measurements on an Experimental Compound Interferometer Antenna, AFCRL-943, Sci. Rpt No. 1, Contract AF19(604)-8059, Stanford Research Institute, Oct. 1961.

37. An Experimental Simultaneously Scanned Antenna System, AFCRL-62-85, Sci. Rpt No. 2, Contract AF19(604)-8006, Hughes Aircraft Co., Dec. 1961. (See also Sci. Rpt No. 1.)

38. L.R. DAUSIN, K.E. MEBUHR, and N.J. NILSSON, The effects of wideband signals on radar antenna design, WESCON Record (Part 1), 1958, pages 40-48.

39. A. KSIENSKI, Signal processing antennas (Part I), Microwave J. 4(No. 10): 77-90, Oct. 1961; (Part II), Microwave J. 4(No. 11):87-94, Nov. 1961.

40. G.B. PARRENT, Jr. and T.J. SKINNER, Diffraction of partially coherent light by a plane aperture, Optica Acta 8:93-102, Jan. 1961; J.I. MASTERS and G.B. PARRENT, Jr., Propagation in laser crystals, Proc. IRE 50(No. 2):230-231 (correspondence), Feb. 1962.

41. R.A. SHORE, Partially Coherent Diffraction by a Circular Aperture, AFCRL-TR-62-715, Aug. 1962; Proc. Symposium on Electromagnetic Waves and Antennas, URSI, Copenhagen, Denmark, June 1962.

42. C.J. DRANE, Jr., and G.B. PARRENT, Jr., On the mapping of extended sources with nonlinear correlation antennas, IRE Tr. Antennas and Propagation AP-10(No. 2):126-130, Mar. 1962.

43. A.C. SCHELL, The variable-capacitance line array, Proc. 9th Annual Symposium, USAF Antenna R&D Program, Monticello, Ill., Oct. 1959.

44. F.C. OGG, Jr., Steerable array radars, IRE Tr. Military Electronics MIL-5(No. 2):80-94, Apr. 1961.

45. H.V. COTTONY and O.C. WILSON, A high-resolution rapid-scan antenna, J. Res., National Bureau of Standards 65D(No. 1):101-114, Jan-Feb. 1961.

46. C.J. SLETTEN, P. BLACKSMITH, Jr., and L.F. SHODIN, Amplitude Scanning of Antenna Arrays, AFCRC-TR-58-124, Mar. 1958.

47. A.C. SCHELL and E.L. BOUCHÉ, A Concentric Loop Array, AFCRC-TR-59-129, Apr. 1959.

48. A.C. SCHELL, A Steerable-Beam Corner Array, AFCRC-TR-59-373, Dec. 1959.
49. J.D. TILLMAN, The Theory and Design of Circular Antenna Arrays, AFCRL-62-63, Contract AF19(604)-4967, U. Tenn., Jan. 1962.
50. C.J. SLETTEN, P. BLACKSMITH, Jr., and G.R. FORBES, A New Method of Antenna Array Synthesis Applied to Generation of Double-Step Patterns, AFCRC-TR-55-108, Sept. 1955; IRE Tr. Antennas and Propagation AP-5(No. 4):369-374, Oct. 1957.
51. C.J. SLETTEN, R.B. MACK, W.G. MAVROIDES, and H.M. JOHANSON, Corrective line sources for paraboloids, IRE Tr. Antennas and Propagation AP-6(No. 3):239-251, July 1958. [See ridge lines, pp. 245-246.]
52. C.J. SLETTEN and W.G. MAVROIDES, A method of side lobe reduction, Side Lobe Conference, NRL Rpt No. 4043, pp. 1-12, Naval Res. Lab., Washington, D.C., Apr. 1952.
53. W.G. MAVROIDES and J.H. PROVENCHER, Off-Axis Sidelobe Reduction in Elliptic Torus Reflectors, AFCRC-TR-58-199, Dec. 1958.
54. F.A. JENKINS and H.E. WHITE, Fundamentals of Physical Optics, McGraw-Hill, 1937, page 122.
55. L.J. RICARDI and L. NIRO, Design of a Twelve-Horn Monopulse Feed, MIT Lincoln Laboratory Rpt No. 315-G-0002, Contract AF19(604)-7400, Mar. 1961.
56. D.P. FLOOD, Electromechanically Scanned Fixed Circular Array, AFCRC-TR-60-107, Final Engrg Rpt, Contract AF19(604)-1554, Andrew Alford Consulting Engineers, June 1960.
57. E.C. FINE, The metal-plate analogue of a Luneburg lens, Proc. 3d Symposium on Scanning Antennas, Naval Res. Lab., Washington, D.C., Nov. 1950, pages 30-33.
58. W. ROTMAN and R.F. TURNER, Wide-angle Microwave Lens for Line Source Applications, AFCRL-62-18, Jan. 1962.
59. J. RUZE, Wide-angle Metal-plate Optics, AFCRC Tech. Rpt No. E5043, Mar. 1949; Proc. IRE 38:53-58, Jan. 1950; correction Proc. IRE 39:697, June 1951.
60. J. BLASS, Multidirectional antenna; a new approach to stacked beams, IRE Intl Conv. Record (Part 1—Antennas and Propagation) 8:48-50, Mar. 1960; Multidirectional-Beam Scanning Antenna Array, RADC-TR-61-38, Final Rpt, Contract AF30(602)-1920, W.L. Maxson Corp., Dec. 1960.
61. J. BUTLER and R. LOWE, Beam forming matrix simplifier design of electronically scanned antennas, Electronic Design 9:170-173, Apr. 12, 1961.
62. F.S. HOLT et al., V-Beam Antennas for Height-Finding, AFCRC-TR-56-115, Dec. 1956.
63. A. ISHIMARU, Theory of unequally spaced arrays, IRE Tr. Antennas and Propagation AP-10(No. 6):691-702, Nov. 1962.
64. A.C. SCHELL and J. MORISON, A technique for power pattern synthesis, AFCRL Electromagnetic Radiation Laboratory Rpt No. CRRD-86, Feb. 1963. To be published.
65. E.K. PROCTOR and C.M. ABLOW, A Variational Method of Synthesizing Antenna Power Patterns, AFCRL-387, Sci. Rpt No. 9, Contract AF19(604)-3502, Stanford Res. Inst., Mar. 1961.

66. J. ROBIEUX and E. SPITZ, (Part I) Research on Air to Ground Scatter, (Part II) Supergain and Volumetric Antennas; AFCRC-TR-59-193, Final Rpt, Contract AF61(514)-1150, Compagnie Générale de Télégraphie Sans Fil, June 1959.

67. R.B. MACK, A Study of Circular Antenna Arrays, Ph.D. thesis in preparation, Applied Science Division, Harvard University, 1963.

68. F.J. ZUCKER, Surface and leaky wave antennas, Chap. 16 in Antenna Engineering Handbook, H. Jasik, Ed., McGraw-Hill, 1961; Electromagnetic Boundary Waves (An Introduction), AFCRL Electromagnetic Radiation Laboratory Rpt No. CRRD-76, Sept. 1962. * To be published.

69. M.E. PEDINOFF, The Negative Conductance Slot Amplifier, AFCRL-920, Sci.Rpt No. 3, Contract AF19(604)-8386, Hughes Aircraft Company, 24 May 1961; W.H. KUMMER, F.G. TERRIO, and A.T. VILLENEUVE, An Experimental Simultaneously Scanned Antenna System, AFCRL-62-85, Sci.Rpt No. 2, Contract AF19(604)-8006, Hughes Aircraft Company, Dec. 1961.

70. A.D. FROST, Parametric amplifier antenna, Proc. IRE **48**:1163, June 1960.

71. G.B. PARRENT, Jr., and P. ROMAN, On the matrix formulation of the theory of partial polarization in terms of observables, Il Nuovo Cimento (Serie X) **15**:370-388, Feb. 1960; AFCRL-362 (reprint).

72. (U)Classified Proceedings of the Second Symposium on the Plasma Sheath—Its Effect Upon Reentry Communication and Detection, 10-12 April 1962, AFCRL-62-537, Sept. 1962. SECRET

AF Cambridge Research Laboratories, Bedford, Mass. Electronics Research Directorate
MODERN ANTENNAS FOR SPACE COMMUNICATIONS by C.J. Sletten. 47 pp. incl. illus.
AFCRL-63-51 February 1963 Unclassified report

Research trends in antenna design stress the probability that space communication and detection functions of future systems will depend on giant-aperture antennas operating at several hundreds of megacycles per second. The design principles and merits of large-acreage antennas such as spherical reflectors, paraboloidal reflectors, parabolic cylinder antennas, flat antenna arrays, and interferometers are reviewed, with particular attention to the new multiplate antenna design. The electronic scanning methods of antennas and arrays that are compared include some advanced designs for nonlinear antennas. New techniques of multibeam generation and antenna pattern optimization are suggested for improving the aperture efficiency and information-gathering capacity of future radio and radar space telescopes. To achieve such desirable improvements, focal region research is important.

UNCLASSIFIED

1. Antennas
2. Antenna configurations
3. Radar antennas
4. Antenna feeds
5. Antenna radiations patterns

I. Sletten, C.J.

UNCLASSIFIED

AF Cambridge Research Laboratories, Bedford, Mass. Electronics Research Directorate
MODERN ANTENNAS FOR SPACE COMMUNICATIONS by C.J. Sletten. 47 pp. incl. illus.
AFCRL-63-51 February 1963 Unclassified report

Research trends in antenna design stress the probability that space communication and detection functions of future systems will depend on giant-aperture antennas operating at several hundreds of megacycles per second. The design principles and merits of large-acreage antennas such as spherical reflectors, paraboloidal reflectors, parabolic cylinder antennas, flat antenna arrays, and interferometers are reviewed, with particular attention to the new multiplate antenna design. The electronic scanning methods of antennas and arrays that are compared include some advanced designs for nonlinear antennas. New techniques of multibeam generation and antenna pattern optimization are suggested for improving the aperture efficiency and information-gathering capacity of future radio and radar space telescopes. To achieve such desirable improvements, focal region research is important.

UNCLASSIFIED

1. Antennas
2. Antenna configurations
3. Radar antennas
4. Antenna feeds
5. Antenna radiations patterns

I. Sletten, C.J.

UNCLASSIFIED

AF Cambridge Research Laboratories, Bedford, Mass. Electronics Research Directorate
MODERN ANTENNAS FOR SPACE COMMUNICATIONS by C.J. Sletten. 47 pp. incl. illus.
AFCRL-63-51 February 1963 Unclassified report

Research trends in antenna design stress the probability that space communication and detection functions of future systems will depend on giant-aperture antennas operating at several hundreds of megacycles per second. The design principles and merits of large-acreage antennas such as spherical reflectors, paraboloidal reflectors, parabolic cylinder antennas, flat antenna arrays, and interferometers are reviewed, with particular attention to the new multiplate antenna design. The electronic scanning methods of antennas and arrays that are compared include some advanced designs for nonlinear antennas. New techniques of multibeam generation and antenna pattern optimization are suggested for improving the aperture efficiency and information-gathering capacity of future radio and radar space telescopes. To achieve such desirable improvements, focal region research is important.

UNCLASSIFIED

1. Antennas
2. Antenna configurations
3. Radar antennas
4. Antenna feeds
5. Antenna radiations patterns

I. Sletten, C.J.

UNCLASSIFIED

AF Cambridge Research Laboratories, Bedford, Mass. Electronics Research Directorate
MODERN ANTENNAS FOR SPACE COMMUNICATIONS by C.J. Sletten. 47 pp. incl. illus.
AFCRL-63-51 February 1963 Unclassified report

Research trends in antenna design stress the probability that space communication and detection functions of future systems will depend on giant-aperture antennas operating at several hundreds of megacycles per second. The design principles and merits of large-acreage antennas such as spherical reflectors, paraboloidal reflectors, parabolic cylinder antennas, flat antenna arrays, and interferometers are reviewed, with particular attention to the new multiplate antenna design. The electronic scanning methods of antennas and arrays that are compared include some advanced designs for nonlinear antennas. New techniques of multibeam generation and antenna pattern optimization are suggested for improving the aperture efficiency and information-gathering capacity of future radio and radar space telescopes. To achieve such desirable improvements, focal region research is important.

UNCLASSIFIED

1. Antennas
2. Antenna configurations
3. Radar antennas
4. Antenna feeds
5. Antenna radiations patterns

I. Sletten, C.J.

UNCLASSIFIED